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Short-Term Operational Forecasts of Trafficability

George Mason, Richard Ahlvin, and John Green

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Geotechnical and Structures Laboratory

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by George Mason, Richard Ahlvin, John Green

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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Contents

Preface

This report describes models developed to predict moisture migration in soil for the purpose of predicting vehicle trafficability and determining tractive force and speed relationships for vehicles.

The study reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Mobility Systems Division (MSD), Vicksburg, MS, under U.S. Army Corps of Engineers RDT&E 6.2 Research. Technical transfer of the code and additional research regarding temporal and spatial stability of code was also conducted under RDT&E Research.

The study was conducted by GSL under the general supervision of Dr. Michael J. O'Connor, Director, and under the direct supervision of Dr. David Horner, Chief, Mobility Systems Branch (MSB).

The field test program was directed by Mr. Dennis Moore, MSB, GSL. Messrs. Richard Tennant and David McClurg, MSB, provided field test support. Messrs. Richard Ahlvin, George Mason, and John Green developed the programs and algorithms. Messrs. Mason, Ahlvin, and Green prepared this report.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

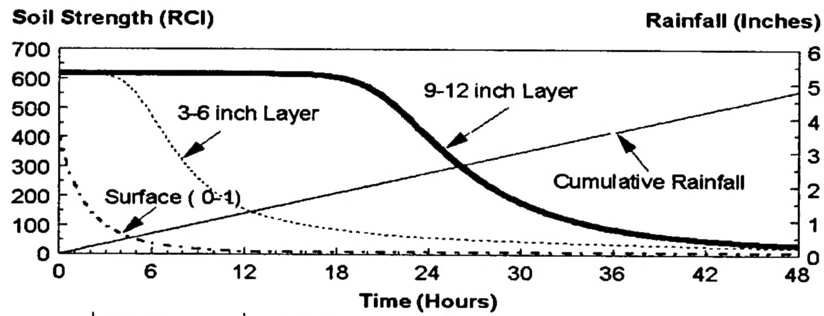
Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	0.006894757	megapascals
pound (force) per foot	14.5939	newtons per meter
square feet	0.09290304	square meters
square inches	0.00064516	square meters
square miles	2,589,998	square meters
square yards	0.8361274	square meters
tons	907.1847	kilograms
yards	0.9144	meters

Executive Summary

The primary objective of this study was to extend current state of the art for predicting temporal changes in soil strength as it relates to vehicle traction. A secondary objective was to develop an algorithm which could be included in high-resolution combat models for improvement of modeling weather effects on mobility. To this end, the algorithms developed in this study were included in the Semiautomated Forces (SAF) models, specifically JointSAF 5.4. This provided an approach to evaluating combat models in the context of weather effects on mobility.

Two models are developed. The first is the Short-Term Operational Forecasts of Trafficability (SOFT) model. The second Real-Time Mobility (RTM) Model is a vehicle movement model which reacts to continuous changes in soil strength. A model run with SOFT under heavy rainfall conditions of 0.10 in./hr of rain with a clayey silt soil type (ML) is shown following this paragraph. In this scenario, neither runoff nor evaporation were introduced. Soil strength drops rapidly from a hard packed materiel of 625-cone index to an area that will cause immobilization of many military vehicles within a 23-hr period. The SOFT is a layered model, and predictions were made for the surface, for 3- to 6-in., and 9- to 12-in.[1] layers. The table provided with the following figure indicates the soil strength at which an M1A1 main battle tank and a Grizzly mine plow vehicle will become immobilized.

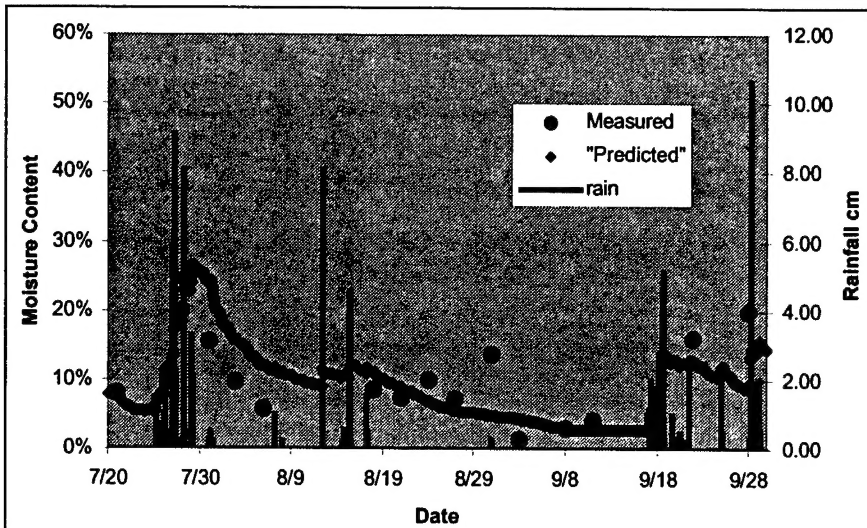
[1] A table for converting non-SI units of measurement to SI units is presented on page vi.



	One Pass	Fifty Pass
M1A1	26	59
Grizzly	28	65

Simulated variations with soil strength with climate conditions

To evaluate algorithms adopted from past climatic studies and those used in this report, study sites were selected and monitored. The predicted versus measured percent moisture content for surface readings at Fort Leonard Wood, Missouri, are shown in the illustration following this paragraph. The computations were made for a 3-month period and compared to field measurements by the U.S. Geological Service (USGS). Percent moisture content, measured as a function of the weight of the soil, is plotted on the first y-axis. Rainfall in centimeters is plotted on the second y-axis. Rainfall is illustrated by the bar graph. The continuous line illustrates the predictions. The points are measured values in irregular intervals. This plot represents the surface layer and illustrates a good agreement for the model predictions.



Predicted versus measured moisture content

1 Introduction

Background

On November 30, 1994, Major General Joe N. Ballard, U.S. Army (Headquarters, Department of the Army 1989), detailed the requirements for collection and dissemination of information required for U.S. Army Engineer terrain teams to determine the weather requirements for current models used by the U.S. Army Corps of Engineers to forecast vehicle trafficability. These requirements included the collection of data from a weather station. Substantial issues still existed regarding the virtual and constructive environments and the approach to implementation of the Operational Requirements Doctrine (ORD) for the live environment.

a. What are the time constraints for predicting soil moisture?

b. How do these time constraints correlate with respect to the size of the military unit that is modeled?

c. What is the range in depths required for predicting mobility?

d. What depths of moisture influence wet-slippery conditions for mobility?

e. How does vegetation and slope impact these predictions?

f. Are these mobility models integrated into current training models?

The Army's weather collection and forecasting program is entitled Integrated Meteorological System (IMETS). The IMETS provides forecasts of weather conditions. The IMETS program will be supplemented with tactical field weather stations such as the Tactical Meteorology Station (TACMET) or Automatic Meteorological Sensor System (AMSS). These weather stations will transmit information that consists of:

a. Wind speed and direction.

b. Temperature.

c. Humidity.

d. Barometric pressure.

e. Rainfall rate and amount.

f. Soil temperature and moisture.

g. Solar radiation.

h. Illumination.

The U.S. Army Engineer Research and Development Center (ERDC) was funded to research algorithms pertaining to Short-Term Operational Forecasts relative to vehicle mobility. This workunit is an extension of previous research in which the Soil Moisture-Strength Prediction (SMSP) system was developed.

The SMSP predicts daily forecasts of ground strength for purposes related to trafficability. The short-term forecasting was created to extend the SMSP algorithms to consider temporal changes in moisture content of the soil at intervals of hours and minutes. These short-term forecasts were developed to support efforts in the live and virtual environment included in this report as Appendices A through E.

Objectives

The main objective of this study was to develop and verify a model that predicts short-term moisture migration in a soil, which ultimately affects vehicle mobility. The report will describe in two major areas: the first is development of a model to predict moisture/soil strength in short time and spatial increments, the second is development of a vehicle mobility model which will give quick answers to reductions in speed due to rapid soil strength changes. The validation tests utilized three soil types; a clay, silt, and sandy clay at various compacted states. The soil areas were measured during actual rainfall events and artificial rainfall events. The artificial events were considered to induce more rapid changes in the soil moisture. A model was written and integrated into the Semi-Automated Forces (SAF) environment to replicate the soil behavior.

Two basic models were developed. The first model, Short-Term Operational Forecasts of Trafficability (SOFT), was a soil physics model, defining moisture changes of the soil with respect to long-term and short-term weather changes. The SOFT model extended the Soil Moisture-Strength Prediction (SMSPII) algorithms described by (Morris 1994). The SOFT model extended the SMSPII model, which operated at 24-hr time intervals and 15-cm (6-in.) spatial intervals to include changes in the time intervals of 1 min and spatial intervals of 1 cm. The SOFT also includes a modified evaporation model. The second model, the Real Time Mobility Model (RTM), is a vehicle traction model from the soil parameter outputs of the SOFT. These models are supported through additional coding which transfer information within the high-resolution combat model JointSAF. The output of SOFT is moisture content and soil strength (in terms of Rating Cone Index (RCI)) for the surface and subsurface layers. Figure 1 illustrates the various models and data dictionaries required to run the RTM and SOFT. The box confines those models which run internal to SAF as libraries of concurrently run executables. The NATO Reference Mobility Model (NRMM) main module is run external to SAF to provide preprocessed output of vehicle information. This preprocessing of information is conducted to reduce run time requirements.

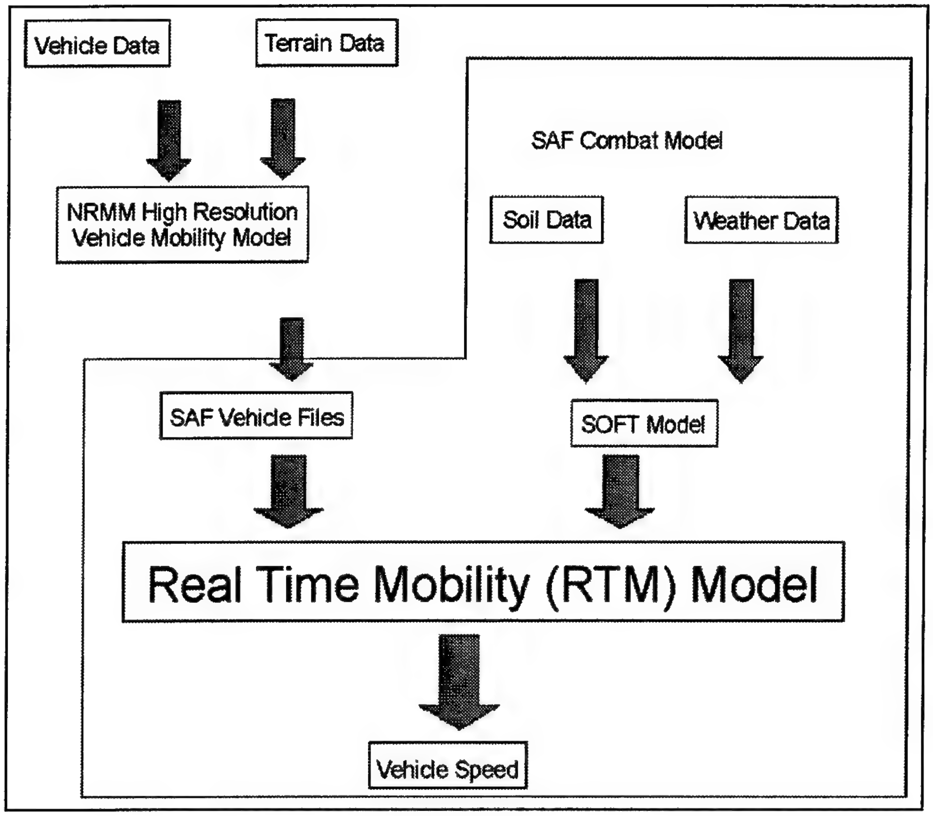


Figure 1. Flowchart of SOFT integration with RTM in SAF

Scope

The requirements necessary to achieve the objectives of this assessment were as follows:

a. Laboratory data were collected at each site for soil information to include specific gravity, clay content, Atterberg limits, and moisture content by weight.

b. At each site, density, cone index, and moisture were recorded at varying time intervals.

c. An Application Programmers' Interface (API) was written for the SOFT model.

d. An API for mobility, which reads output from SOFT, and predicts vehicle speed.

2 SOFT Formulation

Introduction

A model entitled SOFT is proposed for the prediction of dynamic changes in the physical properties of soils. These physical properties are then used to predict a soil strength measurement (cone index). The cone index calculation is used to predict trafficability of wheeled and tracked vehicles. The model predicts cone index as a function of moisture migration through a layered soil at discrete time and spatial intervals. The prediction is performed for intervals of 30 min or less and vertical spatial intervals of 1 cm.

The soil strength is defined in terms of cone index as a function of soil type, moisture content by weight, and soil density. Soil strength is predicted to a depth of 30 cm at varying intervals. The model includes algorithms for sorptivity of the surface, migration of the wetness front, and runoff during nonfreezing periods. The SOFT model is imbedded in a standalone program called Hydrosim (Mason 2000). The Hydrosim uses SOFT to dynamically change soil strength and moisture content attributes in the terrain database within the SAF model for the Compact Terrain DataBase (CTDB) version 7.0.

Two vehicle files were created using NRMM to model a generic wheeled and tracked vehicle. This study illustrates a method of dynamically changing moisture content of the soil within the SAF, while effecting movement rates of vehicles. The vehicle database for the tracked vehicle includes plow forces as a function of soil strength and soil type. These were preprocessed forces as derived from the NRMM (Farr et al. 1991).

Background

Mobility and countermobility predictions for regional areas of the world require knowledge of terrain and the vehicle system. The soil strength required to sustain traffic can be measured with a cone penetrometer. The cone penetrometer has been considered the standard for predicting vehicle trafficability for the U.S. Army since the late 1940's. The soil strength will change based upon the physical state of the soil, including whether the soil is frozen or in some state of freezing/thawing (Bekker 1969). The information on the strength of the soil in terms of Rating Cone Index (RCI) is then used to predict the maximum vehicle

speed using existing traction models for high-resolution models (Haley, Jurkat, and Brady 1979).

High-resolution combat models have been developed which require accurate predictions of a maximum vehicle speed as a function of terrain and weather. The Hydrosim model developed by the Defense Modeling and Simulation Office (Cornish and Li 1998) used preprocessed data to define saturated zones in the terrain. Environmental Change Notices (ECN) were used to dynamically modify terrain attributes from one soil moisture state to another. These new attributes were added to the CTDB's Polygon Attribute Tables (PAT) which were used to define a new speed of the vehicle. Four soil states were identified by the Hydrosim 1 work (dry, average, wet, and wet-slippery). This version of Hydrosim worked with files generated from ARC INFO which delineated saturated areas based on slope. To this end, Hydrosim categorized areas of the CTDB, defining areas in terms of their level of saturation during various weather conditions external to the weather editors within the combat model.

The Hydrosim model was extended (Mason 2000) to include a model that changed soil strength directly, as a function of changing weather conditions within the JointSAF. The SOFT model was developed to predict the changes in moisture content of the soil. A particular requirement for SOFT was the need to provide soil strength information to model a mine plow vehicle. This required modeling changes in soil strength with depth to predict both traction and plowing forces.

The integration of a soil physics model into Hydrosim provided predictive capability of continuous changes in simulated conditions on the battlefield. The SOFT model was directed at the time and spatial resolution defined in JointSAF. This required modifications of the current soil moisture codes to accommodate the higher temporal and spatial resolutions. The algorithms developed in this study include unsaturated conditions of the soil and do not include snow cover, frozen, freezing, or thawing ground.

Model Formulation

The SOFT model formulation relates *in situ* soil strength variations to the physical properties of the soil (i.e., soil type, moisture content, overburden pressure, and density of the soil). Equation 1, as given by the RCI rating, gives an empirical relationship between soil moisture by weight and the bearing capacity of the soils, as defined by Morris (1994).

$$RCI = e^{[a - b \ln (m)]} \tag{1}$$

where

RCI = soil strength in terms of Rating Cone Index

a, b = coefficients specified for each Unified Soil Classification System (USCS) soil type (Table 1)

m = moisture content (percent (weight (soil/water))

The relationship between moisture content in weight (as opposed to volumetric moisture content) and the dry density of the soil is given in Equation 2.

$$\gamma_d = \frac{SG_s}{S + mG_s}\gamma_w \tag{2}$$

where

γ_d = dry unit weight of soil (lb/ft^3)

γ_w = unit weight of water (lb/ft^3)

S = percent saturation

G_S = specific gravity of solids

The relationship of moisture content of the soil and dry density is given in Equation 3.

$$m = \frac{V_w \gamma_w}{V_s \gamma_d} \tag{3}$$

where

V_w = volume of water (ft^3)

V_S = volume of solids (constant) (ft^3)

Density of the soil is required to determine moisture content by weight and to compute soil strength. The interdependencies of density and volumetric movement of water directly determine soil strength relative to traction of a vehicle.

Water budget routine

The expected values of γ_d are given in Table 1 for various soil types. The volume of water in the soil at any time is determined with a water budget routine as given in Equation 4.

$$V_{w[t,d]} = V_{w[t-1,d]} + \partial V_{w[t,d]} \tag{4}$$

where

t = time (sec)

d = distance (cm)

Given a multilayer system as shown in Figure 2, the volume of water at each interval can be computed as given in Equation 5.

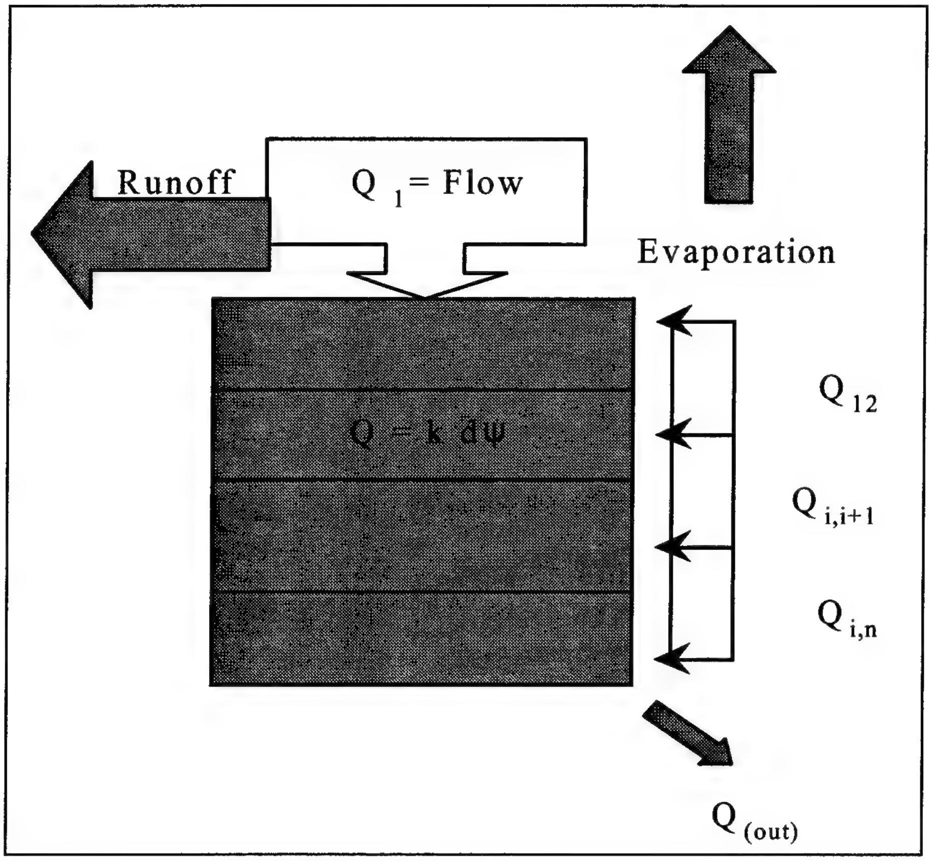


Figure 2. Multilayered soil system

Equation 5 splits the computations into three discrete computations. The first computation is for the change in the volume of water in the surface layer. The second computation for change in water volume can be subdivided into multiple layers. The third computation represents the change in the volume of water in the n^{th} layer where the drainage into the soil and the water table is the only controlling factor. The Sellers (Sellers et al. 1986) equation is modified in Equation 5 with the term d to account for variations of the soil depth.

$$
\begin{aligned}
\partial V_{w[t,1]} &\approx \partial V_{w[t-1,1]} - \left(Q_{(1,2)} \frac{d_1}{d_2} + E + R \right) \partial t \\
\partial V_{w[t,i]} &\approx \partial V_{w[t-1,i]} - \left(Q_{(i,i-1)} \frac{d_{i-1}}{d_i} + Q_{(i,i+1)} \frac{d_i}{d_{i+1}} \right) \partial t \\
\partial V_{w[t,n]} &\approx \left(Q_{(i-1,i)} \frac{d_{i-1}}{d_i} - Q_{(out)} \right) \partial t
\end{aligned}
\tag{5}
$$

where

Q = flow through a layer (LT-1)

E = evaporation at the near surface (LT-1)

R = runoff of the surface Layer (L)

The term (Q) accounts for flow between two consecutive layers of soil, including flow of water up or down in the system. The highest value of the flow is restricted to the saturated permeability of the soil as given in Table 1. The flow is a function of pressure and permeability of the soil. The change in pressure between consecutive layers of soil controls the direction of the flow. The change in flow between layers is given in Equation 6 as a function of relative permeability and pressure.

$$
\partial Q = 2K_r \left(\frac{\partial \psi_{i,i+1}}{d_i + d_{i+1}} + 1 \right) \tag{6}
$$

where

K_r = relative permeability (cm/sec)

ψ = bubbling pressure head (cm)

The bubbling pressure can be measured in the field with a tensiometer and the saturated permeability with a permeameter. The relationship between moisture content, bubbling pressure, and permeability is given by Clapp and Hornberger (1978) in Equations 7 and 8, where the coefficients for β are given in Table 1. Plates 1 and 2 illustrate the relationships between the physical properties of a soil and permeability. Plate 2 illustrates the relationship between S and ψ.

$$
K_r = K_s S^{(2\beta+3)} \tag{7}
$$

$$
\psi_r = \psi_s S_i^{-\beta} \tag{8}
$$

where

β = empirical coefficient from Table 1

Rada, Schwarz, and Witczak (1989) used these relationships to address issues of migration of moisture in a road's subgrade for purposes of defining seasonal road deterioration.

The equation for the output flow Q_r from the final layer is given by Equation 9 (Sellers et al. 1986) as:

$$Q_r = \sin(s)\, K_r \tag{9}$$

where s = slope of the terrain (%).

The slope for this equation is based on digital elevation data. Q_r assumes the soil layer (r) extends to the water table.

Surface layer

From a slipperiness standpoint, researchers are often concerned with only the surface layer of soil. This is particularly true when we consider short-term forecasts of less than 1 day in a region where dry weather has prevailed. When the precipitation events occur, slippery conditions on the surface reduce mobility considerably. To predict surface slippery conditions, a sorptivity term is introduced. Sorptivity is a measure of the surface layers ability to absorb or release water. Computation of the sorptivity of the surface layer will define the amount of water the soil will take in over small increments of time. The equation for sorptivity as given by Clapp and Hornberger (1978) is shown in Equation 10 for zero pressure. Zero pressure indicates that there is no head or standing water to influence permeation.

$$\Omega = (2K_s \psi_s S)^{1/2}(1-W_i) \tag{10}$$

where

Ω = sorptivity at surface pressure of 0 (cm/sec $^{0.5}$)

S = saturation (%)

W_i = moisture content

The sorptivity is related to volume of water absorbed by the soil per unit time. Equation 11 expresses sorptivity, permeability, and time as a function of flow into the surface (Sellers et al. 1986).

$$\partial V_1 = \Omega \partial t^{1/2} + K_{r[1]} \partial t \tag{11}$$

Temperature relationships

The viscosity of water is affected by temperature. This relationship is illustrated in Plate 1. The relationship between permeability at temperature T was fitted for this report to data given by Spangler and Handy (1984). Equation 12 is the resulting fitted formula.

$$K_{20^\circ C} = \frac{\mu T}{\mu_{20^\circ C}} K_T \tag{12}$$

Evaporation rate

The evaporation rate used for this model was designed around the input data available in the SAF environment. The initial derivation of the Penman model, given in Equation 13, Penman (1948), appeared adequate for this experiment. The more advanced energy balance equations require inputs of solar radiance and cloud cover.

$$E = C * (e_s - e_a) u_2^{0.76} \tag{13}$$

where

E = evaporation rate (millimeters/minute)

e_s = saturated vapor pressure (Pa)

u_2 = wind velocity at 2 m above the ground (m/sec)

e_a = vapor pressure (millibars)

C = constant

The vapor pressure at the surface e_s is a function of the percent saturation (S) of the surface. The relationship between atmospheric vapor pressure and saturated vapor pressure as a function of relative humidity is given in Equation 14.

$$E = C * e_a * (1 - h) u_2^{0.76} \tag{14}$$

where h = relative humidity e_a/e_s. Rate of evaporation is used in a time dependent model. Pan evaporation rates were used to correlate predicted and measured evaporation rates and compute the constant C. The constant C was computed at $1 * 10^{-5}$.

Rainfall-runoff modeling

Runoff coefficients were used for rural areas (Schwab et al. 1971) as given in Table 2. The coefficients are applied against the precipitation rate before interception of the ground. Equation 15 gives the new precipitation rate.

$$P = PA - CPA \tag{15}$$

where

P = precipitation rate (LT-1)

A = area of polygon

C = runoff coefficient

Summary

A flowchart for the algorithms above is given in Figure 3. A short-term forecasting algorithm is presented that provides a method to dynamically change soil strength. The static parameters required to run this model are presented in Table 1. Parameters for Table 1 are taken from Rada, Schwarz, and Witczak 1989. These are included in the API. The model accounts for tensions of the soil during seasonal changes in weather which create negative pore pressures that can be measured with field instruments such as tension meters. Positive pore pressures associated with confined aquifers, dynamic loading of the soil, or other pressures are not considered in this formulation. The SOFT model provides a simple method for predicting moisture migration in undisturbed surface layer soils.

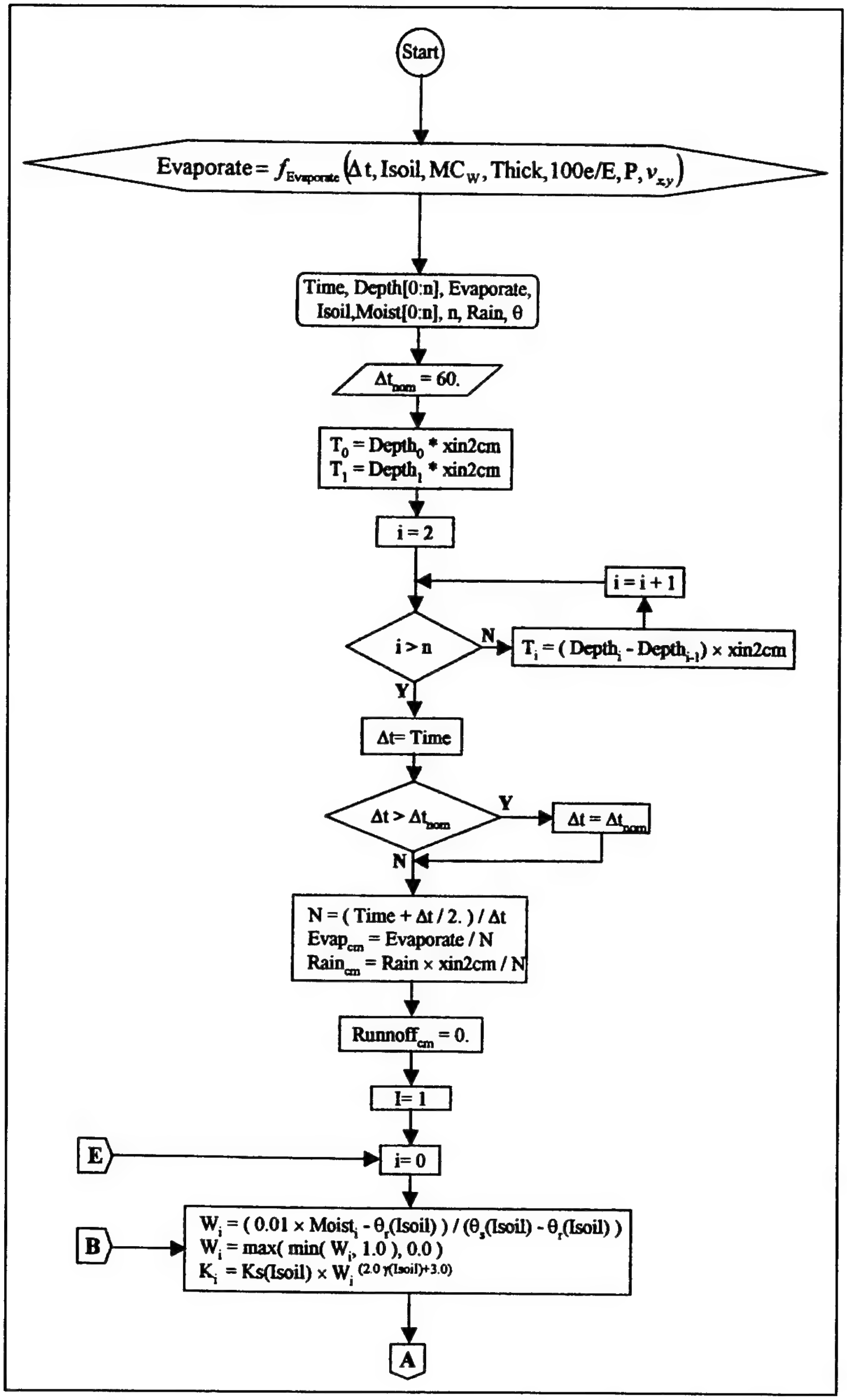


Figure 3. Flowchart of SOFT (page 1 of 4)

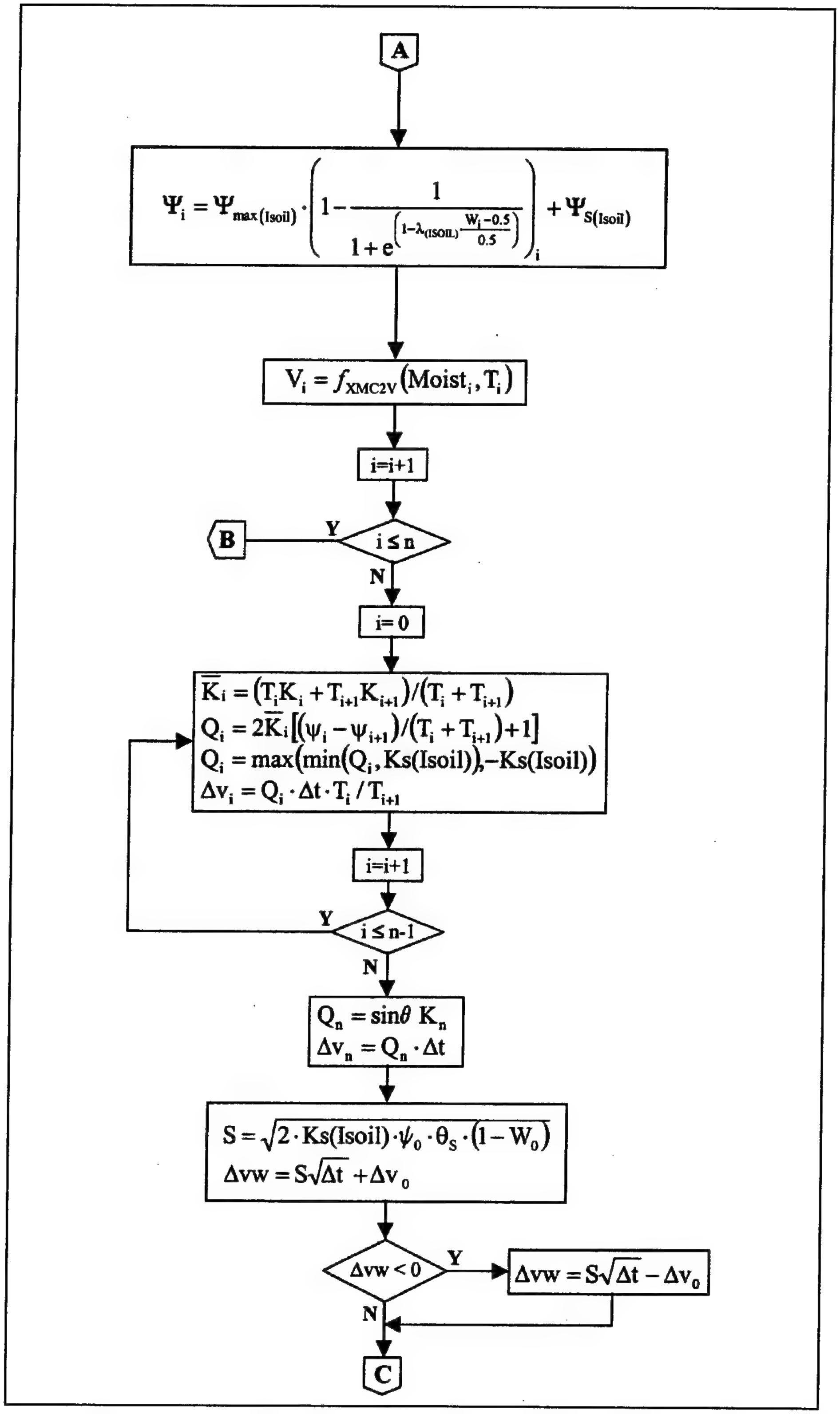


Figure 3. (page 2 of 4)

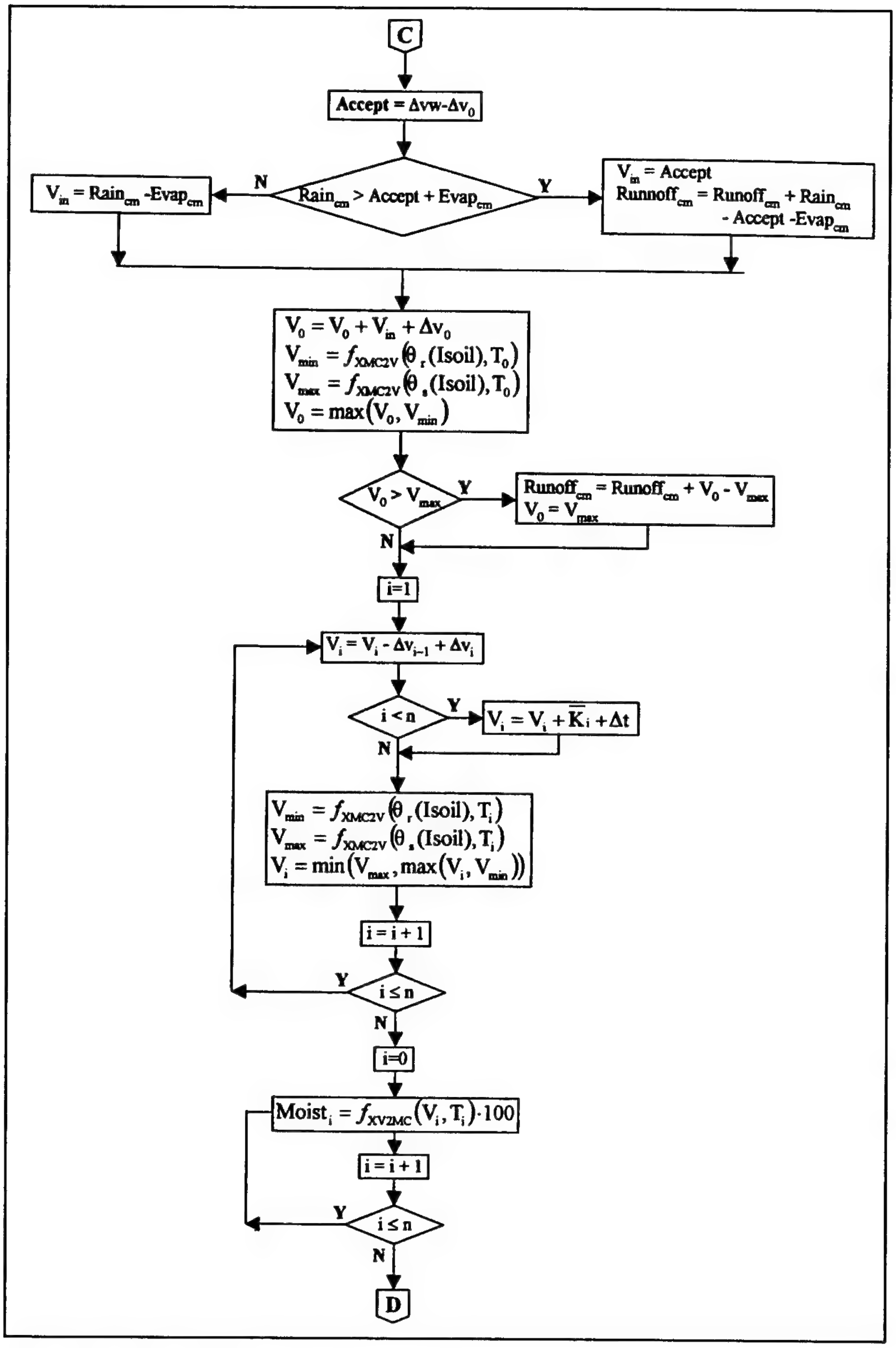


Figure 3. (page 3 of 4)

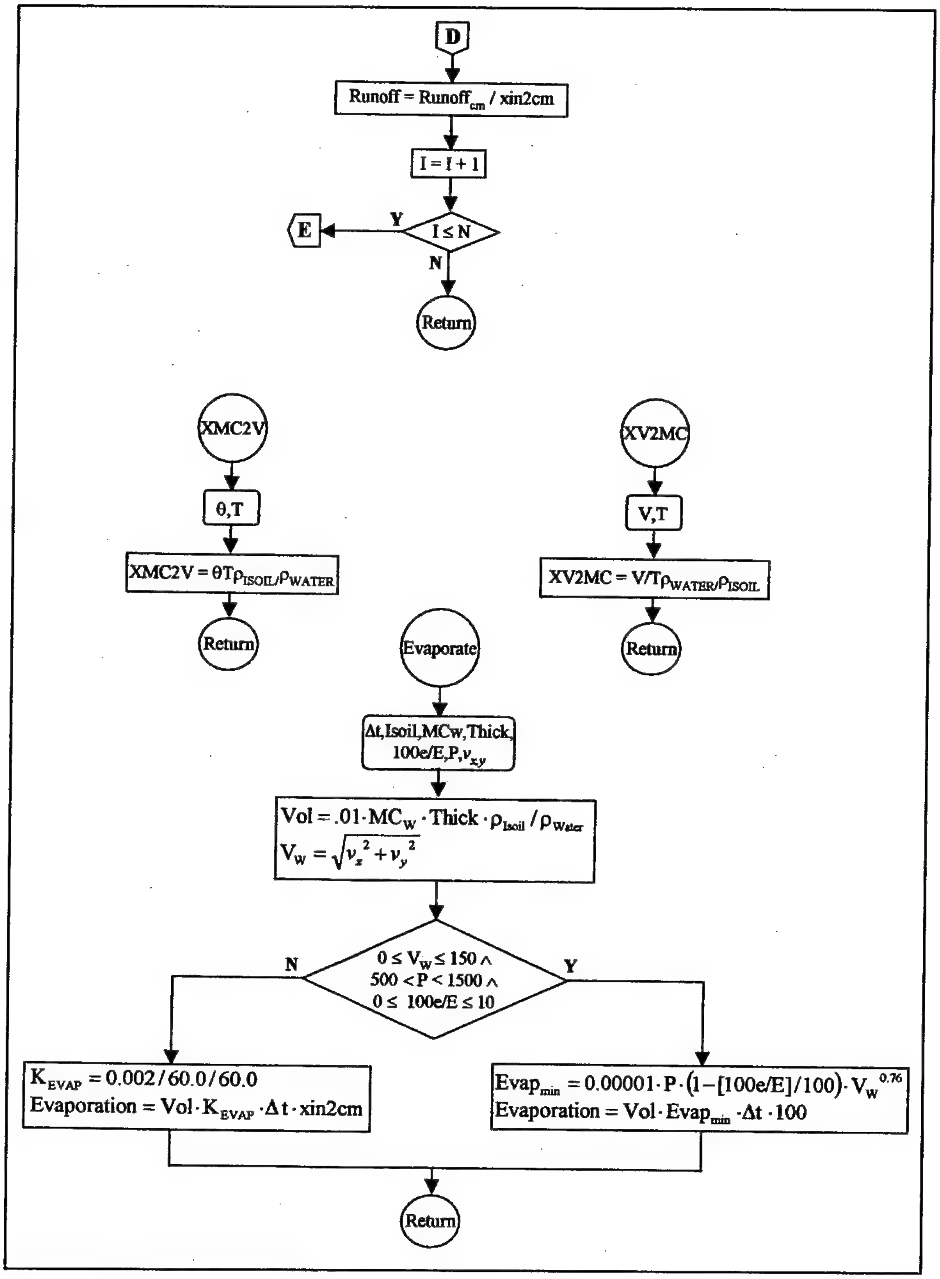


Figure 3. (page 4 of 4)

3 Field Research

Introduction

A limited validation effort was conducted to test the equations implemented for SOFT against field data collected at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, Mississippi, and Fort Leonard Wood, Missouri. Sites were spilt between long-term and short-term research. Short-term testing was based on artificial flooding of areas to evaluate how quickly soil strength would change as a function of worst-case conditions. Long-term test sites were built around existing weather stations. The weather station data were supplemented with periodic testing of soil strength. In both cases, model results were compared to test data. This section details the methods used at each site to collect data.

Two sites at Vicksburg, MS, were flooded. Soil strength and moisture content was monitored on varying time intervals. Gradations and pictures of each site are included in Appendix D of this report. The time intervals were recorded and soil strength was measured with a 0.2-in. cone penetrometer.

Site 1 (entitled Poor House property) was located on a soil classified as low plasticity silt (ML). The site was located in an area on the east side of ERDC. Permeability at the site was recorded with a hygrometer and plotted on Plate 3. Plate 3 suggests the permeability of the soil surface, at saturation, is near 9×10^{-5} cm/sec. The Poor House property site was primarily a fill material with fairly uniform soil strength and density when measured in the initial condition.

Approximately 3 in. of surface material was removed, prior to any testing, to ensure minimal runoff and remove surface vegetation and debris. The area was flooded with approximately 2 in. of water and cone indexes were taken after 2.5 hr and then after 24 hr.

Cone penetrometer measurements at Site 1 are illustrated in Table 3. Twenty measurements were made from the surface to a depth of 18 in. The highest, lowest, first standard and second standard deviations, and average cone value from measured values are provided in Table 3. These values represent the initial strength of the soil. The initial predicted cone index is defined from the model by adjusting the empirical coefficients such that the average initial measured cone index and predicted values for depth were similar. Plate 4 illustrates the high, low, and predicted values of the cone index as derived from 10 cone readings in

the left side of the Poor House property test section. The measured moisture content readings at the surface were between 17 and 18 percent of dry weight. The site was located on fill material, and the cone readings were relatively weak.

Table 4 presents initial empirical coefficients inputted for model prediction. The average hydraulic conductivity of the soil was measured at 4.8×10^{-3} cm/sec for the first 6 in. and 4.5×10^{-3} cm/sec for the 6- to 12-in. layer. Plate 3 illustrates the flow measured during a 30-min test series. A 10-cm head of water was applied. The defined input permeability was varied based on field measurements from 5×10^{-4} cm/sec to 9×10^{-5} cm/sec. Similar variations were defined in Table 4. For example, tests were conducted to determine density. Density readings were measured with a Hvorslev Sampler. Dry density measurements averaged 71 lb/ft^3 with a standard deviation of 12 lb/ft^3.

The variations in initial conditions for the ERDC site were used to suggest similar expected variations of the soil physical properties at the Fort Leonard Wood Site (Site 2). No direct measurements of permeability were made at Fort Leonard Wood. The expected variations in initial conditions are defined in Table 5. Moreover, cone index readings were not collected at Leonard Wood.

Predicted and measured values were compared based on the moisture content, and the average values for the empirical coefficients in Table 1 were redefined in Table 4 such that the initial condition matched for Site 1 (Table 5). The coefficients for Site 2 were also modified to match initial conditions (Table 5). Tables 4 and 5 define a distribution of data within expected ranges. The nominal value defines the numeric value used to predict the initial condition. The mean value is based on the defined distribution type. In each case, a triangular distribution was used. The difference between the nominal and mean value are indicative of the skewness of the distribution.

4 Validation of SOFT

Introduction

The field tests were concentrated on validation of the SOFT model. The SOFT validation effort was split between verification of field data and validation of the components of the model. The model components included:

a. Evaporation.

b. Dry density/moisture relationship.

c. Volumetric water content versus water content by weight.

d. Rapid flux of water through media.

e. Long-term movement of water through media.

Data Verification

Initial verification of the model occurred using a flooded field at Poor House property (Site 1) located at ERDC. The top 3 in. of material was removed with a dozer. Twenty sets of cone penetrometer readings were made using a 0.2-in. cone and a 750 dial to allow for follow-on tests or the area would contain water. The cones were punched after the earth was removed. Variations in soil strength are indicated with depth in Plate 4. A set of moisture contents/soil strengths from the prediction model was mapped to these initial conditions. Table 6 provides the initial conditions for the SOFT model. Predicted versus measured cone index readings are given in Table 3 and plotted in Plate 4. These initial conditions had significant effect on predicted temporal changes in the soil. If initial conditions were defined at too low a moisture content, the time required for the water to flow through the media was rapid and saturation would occur in a rapid manner. Likewise, if the initial condition for the soil was too dry and the respective initial soil strength defined too high, the time for the water travel through the soil was excessive. Defining the initial sequence of moisture contents and respective soil strengths between the standard deviations provided the most reasonable answer.

The entire Site 1 was flooded with a 2-in. depth of water. A water truck was kept onsite during the investigation to assure the water level was constant. Cones were punched into the ground every 2.5 hr. Data from these cones are given in

Table 7. The data are plotted in Plates 5 and 6. For the initial conditions, variations in the cone index readings appeared significant between a depth of 1 and 4 in. The model was run at 60-sec time intervals. Predicted and measured differed at the surface down to 2 in. The model computed rapid absorption on the surface. Initial model predictions were calibrated (initial moisture content was varied within expected ranges) such that the average predicted cone indexes fell between the measured high and low values for 2 in. down to 14 in. At the end of 2.5 hr, cones were punched again and plotted in Plate 5, and these cones indicated good correlations.

The area was then left overnight and at the end of a 24-hr period cones were punched again. The predicted versus measured results are tabulated in Table 8 with Plate 6 illustrating plots of these data. In this series of plots, the surface layer appeared to overlay correctly on the predicted measurements. However, seepage of water into the 5- to 14-in. layer was less than the measured.

Model results from Poor House property were extended to examine results from the Fort Leonard Wood data set. The Fort Leonard Wood experiment was different in as much as only weather station data were collected along with moisture content of the soil. For this program, data collected between July 14 and September 12, 1999, were examined. Plate 7 illustrates wind speed and humidity versus time. Humidity remained relatively high with wind speeds averaging 2 to 3 m/sec. Plots of wind speed and rainfall are given in Plate 8. Since SOFT does not include a freezing model, those times of the year where temperatures dropped below 32 °F were excluded. Table 9 defines the initial conditions used for the model runs.

Predicted and measured evaporation rates are plotted on Plate 9 for nighttime events. Plate 10 illustrates daytime evaporation rates. Both daytime and nighttime evaporation rates were plotted on Plate 11. Pan evaporation rates were used. Prediction of the evaporation rate was conducted using Equation 13. Predicted versus measured is illustrated on Plate 12. There appears to be a good correlation between the predicted and measured values. Solar radiation was not included in this model to maintain simplicity within the model inputs.

A prediction was made for the surface moisture content and plotted on Plate 13. Rainfall data are included in this plot. Some outliers appear during the latter part of August. These outliers appear to be the result of data collection errors. This conclusion is made in part because previous readings showed moisture contents below 10 percent with the outlier at 15 percent. In general, the surface data showed a good trend with the data. This prediction was based on the mean values.

Plates 14 and 15 illustrate predicted versus measured for the 3- to 6-in. layer and 9-to 12-in. layer. Variations in the prediction were within the expected range of the data. The predicted values for this layer did not vary as much as the measured data for a single time series. Errors in field measurements, differences in location of the measured values, and handling the field data may have contributed to the measured variations in data.

Variations in the predictions were introduced in Plate 16, as defined in Table 4, to illustrate the expected prediction values given expected deviations in the initial conditions. These trends appeared to follow expected results and the measured data fell within the minimum and maximum predictions for the layers. Finally, Plate 17 illustrates the 0- to 6-in. accumulation of water over time. The increase in volume of water appears to correspond with the rainfall events.

5 Real-Time Mobility Model

Introduction

Advanced movement algorithms and extended lookup tables are defined in this chapter as an alternative to the limited speed tables which exist in current high-resolution combat and training models. Movement algorithms in the various training models such as SAF (and the high-resolution analytical models) typically have a fixed set of speed lookups that are related to predefined conditions on the battlefield. These conditions cannot be varied without considerable cost in time and effort. However, real-world battlefield conditions that affect vehicle movement are often changing drastically based on changes in weather. The suggested replacement tables for the older version of the JointSAF vehicle files are based on field tests and high-resolution mobility model runs. Field tests have indicated that traction of the vehicle will change based on varying surface and subsurface changes in soil strength. This study discusses the issues of replacing the speed in lookup tables specific to JointSAF with movement algorithms and traction data tables that represent high-resolution model results and field tests. The product of this research was a vehicle model derived from NRMM, which changed vehicle performance as a function of continuous variations of soil strength.

The Defense Mapping and Simulation Office initiated a study (Cornish and Li 1998), which included an investigation of modeling traction and plowing forces of an Army engineer mine-plow vehicle known as the Grizzly. This study included the integration of soil strength and weather effects on terrain (Mason 2000). A subset of the NATO Reference Mobility Model, Version II (NRMM II), was selected as providing appropriate sensitivity and accuracy for the given simulation. An Application Programmer's Interface (API) was designed to facilitate the inclusion of the required functionality without the need to incorporate the entire NRMM[1] model code. Additionally, a principal consideration in the design of the target simulation was to include the effects of weather on mobility performance.

A major factor in mobility performance is the state of the soil surface. In order to incorporate soil strength, or changes thereof, in the SAF environment, a model and an appropriate API called SOFT were developed to predict the moisture condition and subsequent soil strength from rainfall time histories

[1] For the remainder of this document, NRMM is considered synonymous with NRMM II.

(Mason 2000). The SOFT model is essentially a subset of the Soil Moisture-Strength Prediction, Version II (SMSP II) model recast to allow shorter or variable time increments in lieu of the fixed 24-hour period assumed for SMSP II. The SOFT was coupled with a mobility model through an appropriate Federated Object Module (FOM) (Janett et al. 2000). The mobility model currently exists within the JointSAF core libraries. This mobility model takes as input soil type, soil strength, slope, and certain vehicle characteristics to provide a prediction of maximum vehicle speed.

NRMM (Ahlvin and Haley 1992) is a force balance model. The traction-speed relation for the vehicle is determined from the vehicle's power train and traction element characteristics and the current soil type, strength, and surface condition. Various vehicle mobility impediments in the form of resistances are determined. The sum of all impeding resistances is compared with the traction-speed relation. If the traction exceeds the resistance force sum, excess vehicle traction is available and a suitable running speed is determined. Otherwise, if resisting forces are greater than available traction, a vehicle immobilization (NOGO) condition results. Because of limitations in the terrain information available in the target simulation database and vehicle operating mission considerations, several potential mobility impediments including the effects of vegetation, obstacles, ride dynamics, and certain driver reactions normally considered in NRMM were not considered and are not included in the mobility API.

The Traction Model

NRMM incorporates a representation of a vehicle's power train to estimate the vehicle's theoretical power in the form of a maximum available traction versus drive element speed relation. This model requires performance and configuration characteristics of the power train including the engine output torque versus speed (rpm) relation curve, torque converter characteristics (if applicable), transmission gear ratios and efficiencies, and final drive information. Optionally, the theoretical traction-speed relation can be determined through physical testing and provided as an input to NRMM.

The traction-slip relation and soil motion resistance is derived for the given soil type, soil strength, and surface condition. NRMM uses this information to produce a traction-speed relation for the specific vehicle/terrain combination. The fundamental soil relations in NRMM use an empirical system developed at ERDC, which relates vehicle performance to soil strength in terms of RCI for cohesive soils (clays, silts, and wet sands). The semiempirical numeric system relating performance to soil cone index (CI) is used for noncohesive soils (dry sands.)

To reduce the complexity and data volume for the API, a rectangular hyperbola (Equation 16) is fitted to the traction-speed relation using a modified least-squares curve-fit algorithm.

$$s = \frac{a}{t/w + c} + b \tag{16}$$

where

s = speed (mph)

t = tractive-force (lb)

w = vehicle weight (lb)

a, b, & c are the curve fit coefficients (dimensionless)

(The minimum and maximum values of traction from the original relation are also retained.)

An additional power reduction factor may be included to account for the engine accessory loads such as those caused by automatic blade plow depth actuating equipment or breaching equipment. The details (such as duty cycle, etc.) of this load are not modeled; it is known to be substantial (up to 20 percent of engine power). For this implementation, the power reduction is included if plowing is in effect (plowing depth greater than zero.)

A traction reduction factor is also included to simulate the effect of the vehicle running over a disturbed (plowed) surface. The terrain description information (strength information derived from the SOFT model) is valid for in situ soils. It is believed (but unconfirmed by testing) that plowed surfaces should provide less traction than the virgin terrain. Expert opinion is that traction reduction should be at least 10 percent. Similar to the power reduction coefficient, this factor is in effect only during plowing. A comparison of a typical traction-speed relation to the curve fit relation is given in Plate 18.

Plate 19 illustrates the traction relationships of a vehicle as a function of soil strength and vehicle speed. The traction coefficient can relate directly to the vehicle's ability to climb slopes, override vegetation, and negotiate obstacles.

The Resistance Model

External resistance

The resistances considered for the API model are soil motion resistance, resistance resulting from the influence of slope, and resistance derived from the plowing action of a mine plow (or similar) blade operating at a prescribed depth. Resistance resulting from overriding vegetation or obstacles is not considered.

Slope resistance

The effect of slope introduces additional resistance (if traveling up-slope) or additional effective traction (if traveling down-slope.) (In coefficient form, the slope resistance is simply the tangent of the slope.) This value is added to the other resisting quantities.

Plow resistance

The plow resistance coefficient is interpolated from a table of plowing force as a function of plowing depth and soil strength for several USCS soil types. This table may be populated with field test results or information from other simulation models. For this example, the theoretical plowing force model included in NRMM (Farr et al. 1991) was used to populate the data table. Plate 20 depicts this example data.

Plates 21 and 22 illustrate the SAF output as depicted by a "stealth" monitor. The vehicles are placed at the end of a virtual ramp and ordered to the top of the ramp.

The Application Programmers' Interface

The application programmers' interface consists of three primary routines:

Routine	Description
Veh_plow_init	Initialize system and read in performance prediction tables
Veh_maximum_speed	Produce a performance prediction
echo_veh_data	Echo input data to system output

The following is a detailed description of the API routines.

INTEGER FUNCTION VEH_PLOW_INIT(FPATH)

This routine initializes the system and populates the vehicle plow model internal tables from information contained in an external data file.

Input:

FPATH Path name to Vehicle plow performance information data

Outputs:

VEH_PLOW_INIT Initialization status:
0 =Okay
Pos = I/O error; system specific I/O status returned
-1 = Premature E.O.F. reading input data
-2 = No logical unit available for file I/O
-3 = NSTREN out of range [2..MSTREN]

-4 = NPDEPTH out of range [0..MPDEPTH]
-5 = NPSTREN) out of range [2..MPSTREN]
-6 = Unexpected soil type code reading vehicle data
-7 = Soil strength mismatch reading vehicle data
-8 = Unexpected soil type code reading plow data
-9 = Soil strength mismatch reading plow data

Main API call:

SUBROUTINE VEHICLE_PLOWING_SPEED(null, Yin, Plowspeed)

This routine is the primary prediction model. The vehicle maximum speed as a function of the input terrain description is returned.

General note: No data type for Yin was stated in the original API specification. Several of the values are categorical (i.e. Yin(1), Yin(2) and Yin(3)) while the others are analog. Since there are some analog values present, Yin was assumed to be type REAL.

Inputs:
Yin(0) = Blade depth [in] (Note 1.)
Yin(1) = ITD soil type code: (Note 2.)

0 = Unknown	7 = SM	14 = OH
1 = GW	8 = SC	15 = PT
2 = GP	9 = ML	16 = Not Used
3 = GM	10 = CL	17 = Not Used
4 = GC	11 = OL	18 = Not Used
5 = SW	12 = CH	
6 = SP	13 = MH	

Note: and value out of range [1..14] will be assigned 0 (unknown)

Yin(2) = Vegetation cover code:
0 = Bare
1 = Grass
2 = Forest

Yin(3) = CCTT Slope class code:

Code	Range	Value used
1	<= -60	60
2	-40 to <-60	-50
3	-20 to <-40	-30
4	-5 to <-20	-13
5	>0 to <-5	-3
6	=0	0
7	0 to <5	3
8	5 to <20	13
9	20 to <40	30
10	40 to <60	50
11	>= 60	60

Note: Any codes outside the range [1..11] will be assigned 6 (slope = 0)
Yin(4) = Moisture content of surface layer (from SMSP/SOFT) [% by weight]
Yin(5) = Moisture content of soil layer (from SMSP/SOFT) [% by weight]
Yin(6) = Soil strength of surface (from SMSP/SOFT) [CI|RCI]
Yin(7) = Soil strength of soil (from SMSP/SOFT) [CI|RCI]
Output:

Plowspeed = vehicle plowing speed, meters/s (Note 3.)

Notes:

(1) Origin of measurement is not stated. The assumption is made that depth refers to the position (positive down) of the lower-most extremity of the plow unit (i.e., tine tips if plow has tines, etc.) below a flat level ground surface. Negative or zero depth means no portion of the plow blade enters the ground. (2) No table of values for the codes was given. The specification stated "ITD soil codes." The specification for the ITD encoding scheme (MIL-I-89014) shows 16 items for Soil Type Category (STC) values 0 through 15. The assumption is made here that this is the encoding scheme used.
(3) If any input data are unknown, unassigned, or out of range, the plow speed will be set to zero. Codes are produced internally which are related to various types of problems that can occur. However, no mechanism is stated to retrieve and examine these codes externally.

This system is comprised of three sections of vehicle performance information, which is read in from an external data file. (It would be possible to 'hard code' the data tables but that would limit the usefulness of this system.) The prediction is made by interpolating the appropriate information from these tables performing a few computations to provide the needed result.

The first section contains information about vehicle basic performance, which is the tractive force versus speed relation (including all soil influences) and the sum of all vehicle motion resistances for operation on level surfaces (excluding any plowing resistance.) The actual relation is given as the coefficients of a curve-fit hyperbola to the source data. The source data are derived from the NRMM.

The second section is a matrix of plow performance information comprised of resulting plowing forces as a function of soil type, soil strengths, and plowing depths. These data are derived from a combination of field test results and the plowing submodel in NRMM.

The following section describes the format and content of the external data set (data file) read in by the program.

The input data set has three sections of records. Section 1 is basic description information and the arrays of values of the independent variables for the various input tables. This is in FORTRAN NAMELIST format. Section 2 consists of records of vehicle performance information in FORTRAN free-field readable format. The third section, also in FORTRAN free-field readable format, contains

records of information used to populate the internal tables of plow performance information.

VEHDATA

The following are records in FORTRAN NAMELIST format ordered as follows:

Variable	Description
GCW	Vehicle gross combined weight [lb]
HPCOEF	Power-train power reduction coefficient penalty for using plow (1.0=no reduction, 0.0 = 100% reduction)
NPDEPTH	Number of plow data plowing depths given
NPSTREN	Number of soil strengths, plow performance data
NSTREN	Number of soil strengths, vehicle performance data
PDEPTHS(NPDEPTH	Values of plowing depths [in.]
PSTREN(NPSTREN)	Soil strength values for plowing data [CI/RCI]
STCOEF	Surface traction reduction coefficient penalty for operating on plowed surface (1.0=no reduction, 0.0=full reduction)
STREN(NSTREN)	Soil strength values (vehicle data) [CI/RCI]

Section 1. Vehicle Traction & Resistance Performance information

The following are records in FORTRAN free-field format ordered as follows:

Record Number	Surface	Soil-type	Soil-strength
Rec-1	0 (normal)	1 (group1)	STREN(1)
Rec-2	0 (normal)	1 (group1)	STREN(2)
. . .	. . . . .	. . . . .	. . . .
Rec-NSTREN	0 (normal)	1 (group1)	STREN(NSTREN)
Rec-NSTREN+1	0 (normal)	2 (group2)	STREN(1)
Rec-NSTREN+2	0 (normal)	2 (group2)	STREN(2)
. . .	. . . . .	. . . . .	. . . .
Rec-2*NSTREN	0 (normal)	2 (group2)	STREN(NSTREN)
. . .	. . . . .	. . . . .	. . . .
. . .	. . . . .	. . . . .	. . . .
Rec-6*NSTREN	0 (normal)	6 (group6)	STREN(NSTREN)
Rec-6*NSTREN+1	1 (slippery)	1 (group1)	STREN(1)
. . .	. . . . .	. . . . .	. . . .
. . .	. . . . .	. . . . .	. . . .
Rec-2*6*NSTREN	1 (slippery)	6 (group6)	STREN(NSTREN)

Each record is comprised of the following information:

Item#	Fortran Variable	Description
1	IST	Soil strength values (vehicle data) [CI/RCI]
2	CIRCI	Soil strength (checked against values given in STREN)
3	RESCOEF	Vehicle total motion resistance coefficient
4	TFOWMN	Tractive force coefficient value at maximum speed point (i.e., minimum traction)
5	TFOWMX	Tractive force coefficient value at minimum speed point (i.e., maximum traction)
6, 7, & 8	B(i)	Coefficients for curve fit hyperbola of the form: $$TFcoef = \frac{B_1}{Speed + B_3} + B_2$$

Section 2. Plow performance (resistance) information

The following are records in Fortran free-field format ordered as follows:

Record Number	Soil-type	Soil-strength
Rec-1	1 (group1)	PSTREN(1)
Rec-2	1 (group1)	PSTREN(2)
. . .	. . . . .	. . . .
Rec-NSTREN	1 (group1)	PSTREN(NPSTREN)
Rec-NSTREN+1	2 (group2)	PSTREN(1)
Rec-NSTREN+2	2 (group2)	PSTREN(2)
. . .	. . . . .	. . . .
Rec-2*NSTREN	2 (group2)	PSTREN(NPSTREN)
. . .	. . . . .	. . . .
. . .	. . . . .	. . . .
Rec-6*NSTREN	6 (group6)	PSTREN(NPSTREN)

Section 3. Variable description

Each record is comprised of the following information:

Item#	Fortran Variable Name	Description
1	IST	Soil group code
2	CIRCI	Soil strength (checked against values in PSTREN)
3	PFORCES(1,.)	Plowing force [lb] for depth PDEPTHS(1)
4	PFORCES(2,.)	Plowing force [lb] for depth PDEPTHS(2)
.	. . . . . .	. . . .
2+NPDEPTH	PFORCES(NPDEPTH,.)	Plowing force [lb] for depth PDEPTHS(NPDEPTH)

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Table 1
Static Soil Coefficients (after Rada, Schwarz, and Witczak 1989)

USCS Soil Type	ψ_s	k_s	β	Residual Moisture	Saturated Moisture S	Density (lb/ft^3) γ_d	Soil Strength a	Soil Strength b
SW	16.6	.07620	1.852	1.60	34.70	93.6	3.987	0.8150
SP	16.6	.07620	1.852	1.60	24.70	93.6	3.987	0.8150
SM	14.1	.00861	2.375	2.60	40.80	93.7	12.542	-2.9550
SC	18.4	.00384	2.667	5.60	41.90	97.4	12.542	-2.9550
SM-SC	17.2	.00484	2.597	4.80	41.80	100.5	12.542	-2.9550
CL	33.5	.00060	4.505	3.60	46.90	86.8	15.506	-3.5300
ML	33.9	.00079	4.202	2.60	53.70	73.7	11.936	-2.4070
CL-ML	32.9	.00008	4.292	2.60	46.80	83.7	14.236	-3.1370
CH	32.9	.00038	5.208	7.10	47.50	85.5	13.686	-2.7050
MH	39.0	.00004	4.878	3.80	54.70	66.2	23.641	-5.1910
OL	28.6	.00122	3.876	3.00	62.70	77.4	17.399	-3.5840
OH	29.3	.00088	4.237	4.10	89.20	52.5	12.189	-1.9420
GM	12.7	.09980	3.247	4.10	43.80			
GC	23.2	.00174	4.065	3.40	45.20			

Table 2
Runoff Coefficients (after Singh 1983)

Vegetation	Open Sandy Loam Soil Class (0-6)	Clay and Loam Soil Class(7-9)	Tight Clay Soil Class (10-15)
Woodland (Class 2)++			
Flat (0-1)+	0.10	0.30	0.40
Rolling (2)	0.25	0.35	0.50
Hilly (3)	0.30	0.50	0.60
Cultivated (Class 1)			
Flat (0-1)	0.30	0.50	0.60
Rolling (2)	0.40	0.60	0.70
Hilly (3)	0.52	0.72	0.82
Pasture (Class 0)			
Flat (0-1)	0.10	0.30	0.40
Rolling (2)	0.16	0.36	0.55
Hilly (3)	0.22	0.42	0.60

\+ Slope classes as given by API in Appendix A.
++ Vegetation classes as given by API in Appendix A

Table 3
Initial Conditions

	Depth in Inches													
	0	1	2	3	4	5	6	7	8	9	10	11	12	18
	Measured Cone Index Values													
High CI	600	750	700	600	600	600	525	625	650	625	625	530	550	600
Low CI	300	600	610	550	525	475	475	450	475	500	500	500	525	500
1std CI	528	762.8	678	610	586	566	525	590	611	592	588	532	546	573.4
1std CI	352	643.2	616	570	536	482	485	462	477	490	484	508	524	496.6
Average CI	440	703	647	590	561	524	505	526	544	541	536	520	535	535
	Predicted Cone Index Values													
Initial Pred CI	437	695	665	587	507	495	502	556	507	507	507	507	507	507

Table 4
Model Input Parameters for Site 1

Soil Type ML	Nominal Value	Mean Value	High	Low
Saturated Permeability	2.27E-04	9.00E-05	5.00E-04	9.00E-05
Bubbling Pressure	2797%	33.9	35	15
Saturation Moisture Content	45%	45%	50%	40%
Residual Moisture Content	3%	3%	5%	2%
BETA Relationship factor for Pressure versus Permeability	4.735	4.205	6	4
ALPHA Relationship Factor for CI versus w	13.267	13.300	13.400	13.100
GAMMA Relation Factor for CI versus w	-2.407	-2.402	-2.400	-2.420
Dry Density of Soil	75.0	75	80	70
Density w	69.4	69.4		
Time (sec)	60.00	60.00		
Slope	0.00	0.00		
Specific Grav	2.71	2.71		

Table 5
Model Input Parameters for Site 2

Soil Type CL	Nominal Value	Mean Value	High	Low
Saturated Permeability	3.7E-06	1.00E-06	1.00E-05	1.00E-07
Bubbling Pressure	14.0	15	20	7
Saturation Moisture Content	40.0%	40.0%	45.0%	35.0%
Residual Moisture Content	2.5%	2.0%	4.0%	1.5%
BETA Coefficient for Pressure versus Permeability	4.50	4.51	4.80	4.20
ALPHA Factor for CI versus moisture content	15.502	15.506	16.000	15.000
GAMMA Relation Factor for CI versus Moisture Content	-3.633	-3.600	-3.300	-4.000
Dry Density of Soil	81.7	85.0	90.0	70.0

Table 6 Initial Conditions for Site 1, Poor House Property															
Depth	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**	**11.00**	**12.00**	**18.00**	**Relative Depth to Surface**
Delta Depth	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	10.00	Depth of Layer in cm
Field Min	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.36	Volume of Water in cm
Field Max	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	4.86	Volume of Water in cm
Density	75.00	75.08	75.15	75.23	75.30	75.38	75.45	75.53	75.60	75.68	75.75	75.83	75.90	75.98	Initial Densities
Init RCI	426	677	649	572	495	482	490	542	495	495	495	495	495	495	Initial Cone Index profile

Table 7 Data at 2.5 Hours														
Cone Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**18**
High CI	150	480	620	600	500	510	550	550	650	600	650	650	650	750
Low	70	170	220	320	450	430	450	450	500	500	475	550	550	750
1std	138	410.6	523	560	487	513	556	537	626	600	631	647	647	750
1std	82	181.4	225	368	445	455	484	463	526	524	499	577	573	750
Avg	110	296	374	464	466	484	520	500	576	562	565	612	610	750
Predicted	61	141	301	571	495	482	490	542	495	495	495	495	495	495

Table 8 Data at 24 Hours														
Cone Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**18**
High	0	70	260	350	270	250	220	250	260	260	290	300	350	530
Low	0	10	80	10	120	140	130	130	140	160	130	170	160	250
1std	0	53	249	290	232	221	211	227	245	243	265	267	295	495.6
1std	0	13	128	103	132	151	153	163	159	175	175	189	201	324.4
Avg	0	33	188	196	182	186	182	195	202	209	220	228	248	410
Predicted	61	65	69	72	76	129	186	510	495	495	495	495	495	495

Table 9
Initial Conditions for Site 2, Fort Leonard Wood

Depth	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**	**11.00**	**12.00**	**18.00**	**Relative Depth to Surface**
Delta Depth	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	10.00	Depth of Layer in cm
Field Min	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.33	Volume of Water in cm
Field Max	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	5.24	Volume of Water in cm
Density	92	89	82	82	82	82	82	82	82	82	82	82	82	82	Initial Densities
Init RCI[1]	3000	750	750	150	150	130	130	140	100	100	90	100	250	250	Initial Cone Index profile
Init Moist %	7.9	11.5	11.5	17.9	17.9	18.7	18.7	18.3	20.1	20.1	20.7	20.1	15.6	15.6	Initial Moisture Content

[1] Computed based on soil moisture.

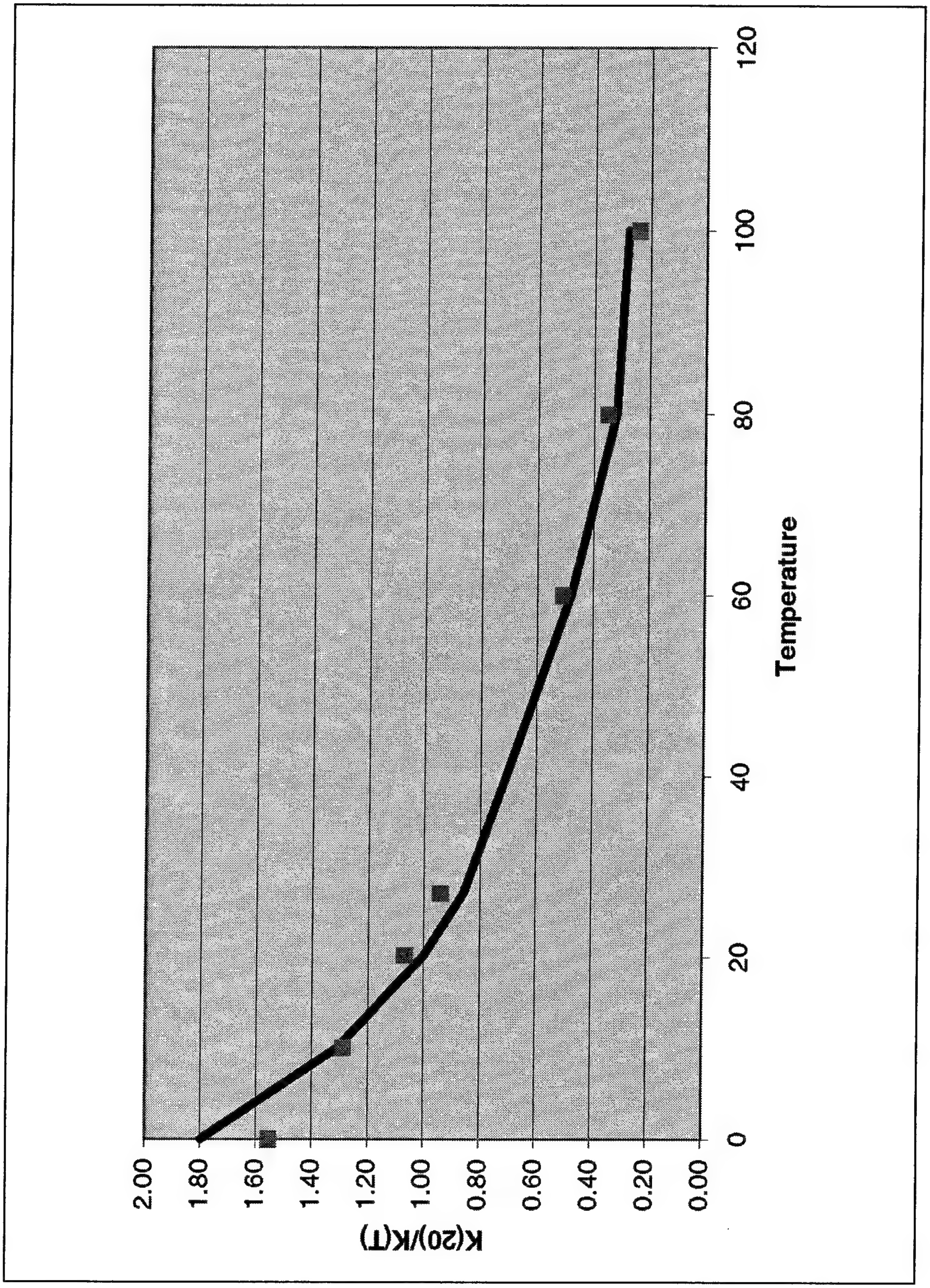
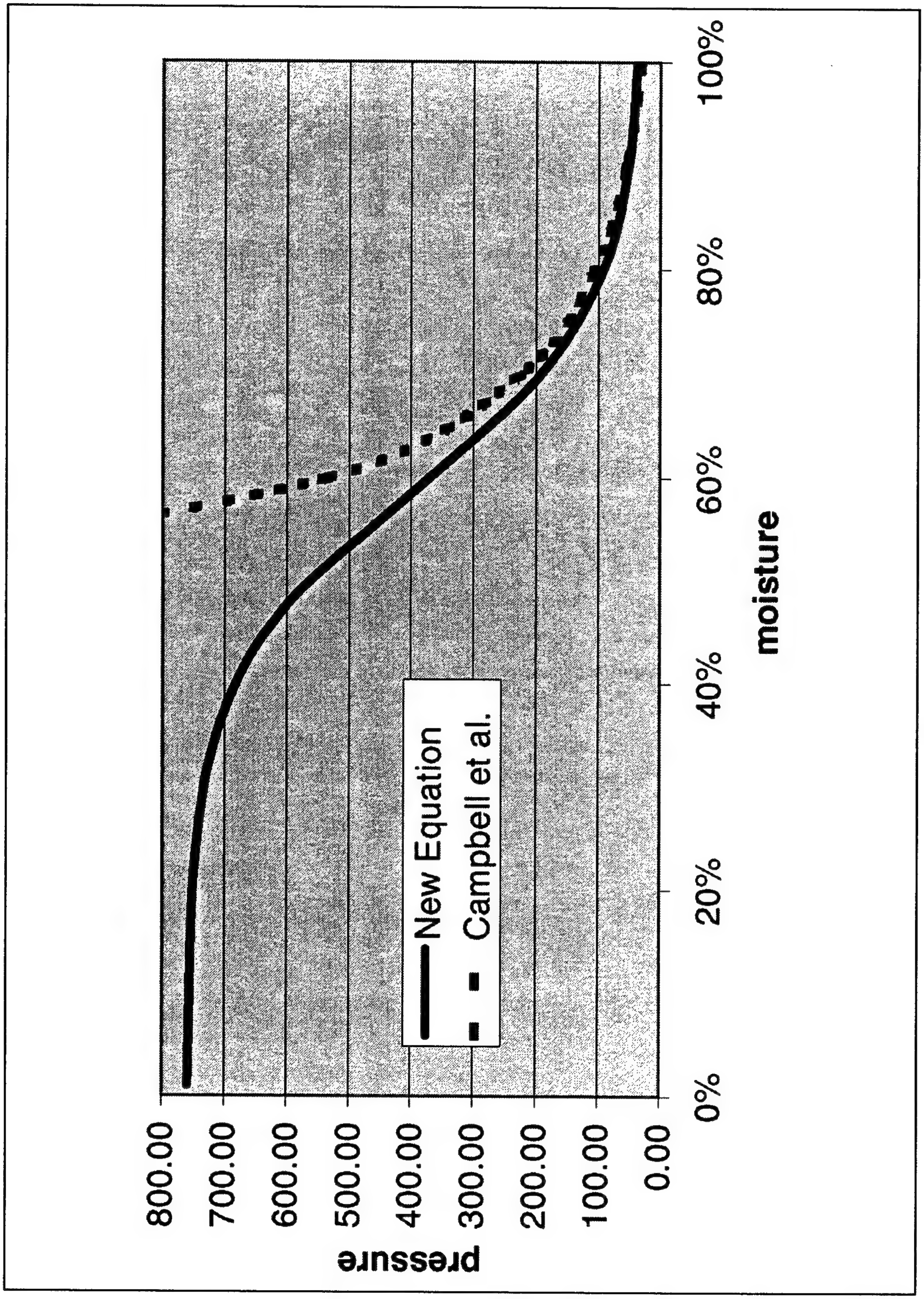

K(20)/K(T)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
20
40
60
80
100
120
Temperature

PLATE 1



pressure
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0%
20%
40%
60%
80%
100%
moisture
New Equation
Campbell et al.

PLATE 2

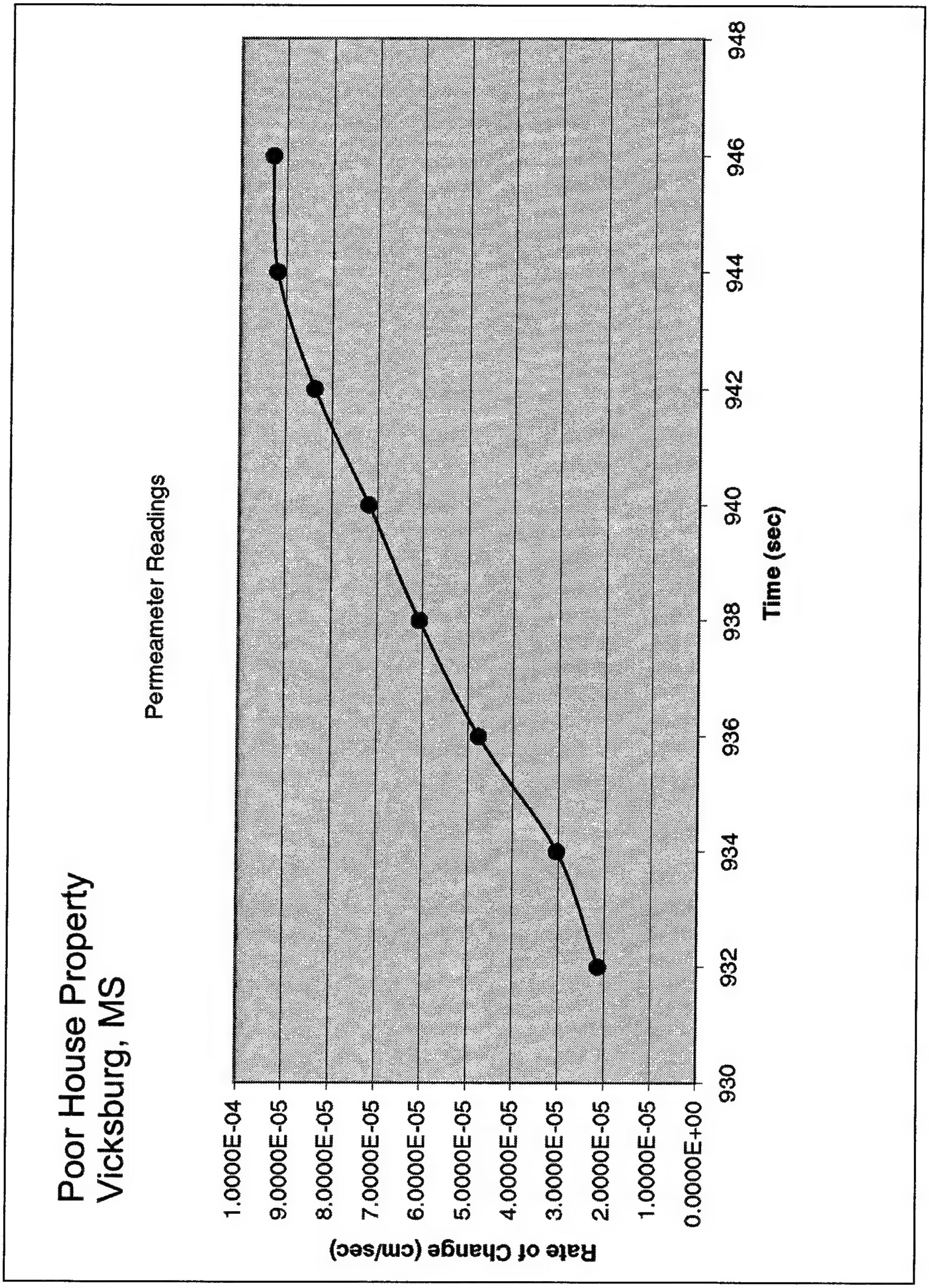

Poor House Property
Vicksburg, MS
Permeameter Readings
Rate of Change (cm/sec)
1.0000E-04
9.0000E-05
8.0000E-05
7.0000E-05
6.0000E-05
5.0000E-05
4.0000E-05
3.0000E-05
2.0000E-05
1.0000E-05
0.0000E+00
Time (sec)
930
932
934
936
938
940
942
944
946
948

PLATE 3

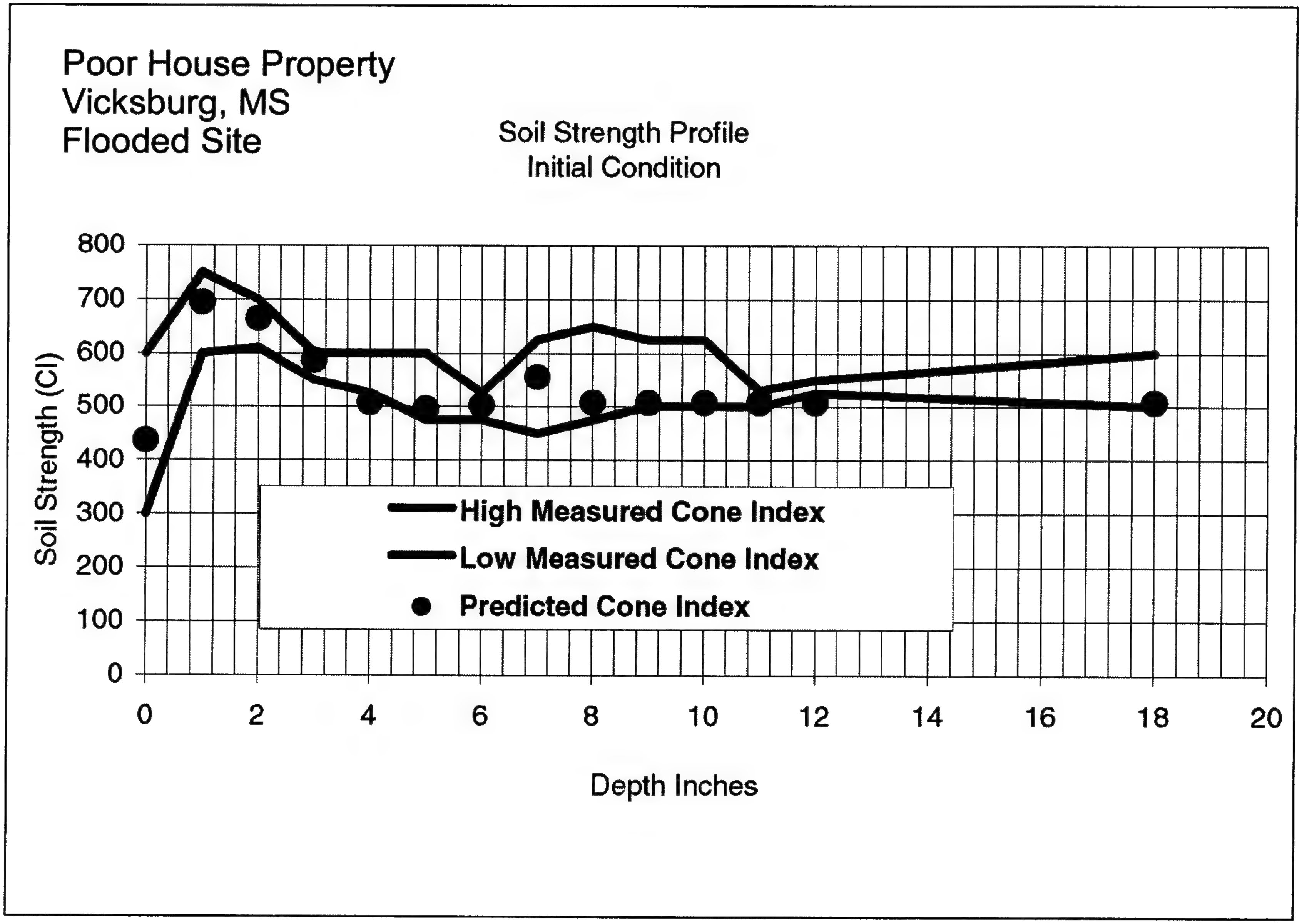
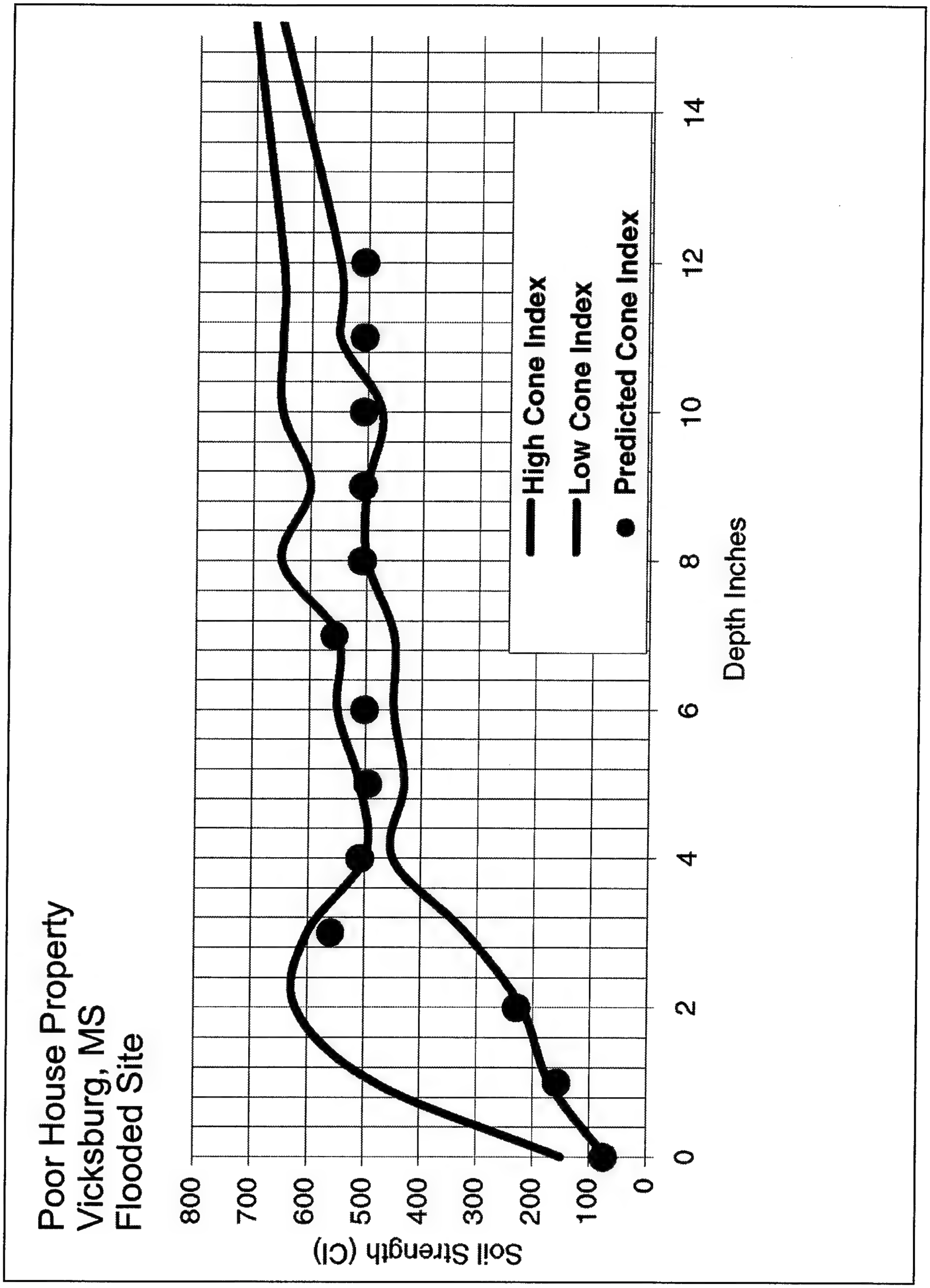
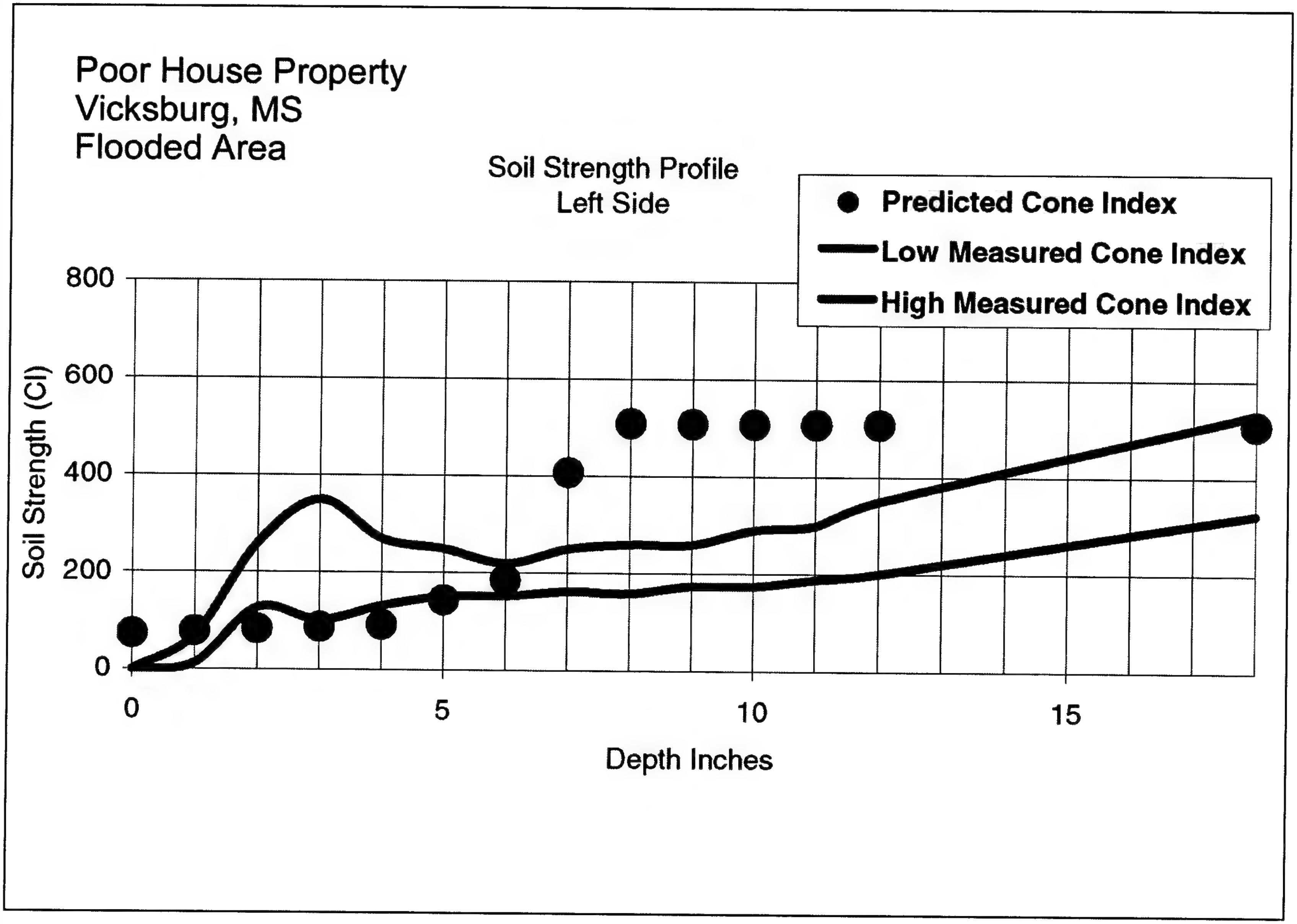

Poor House Property
Vicksburg, MS
Flooded Site
Soil Strength Profile
Initial Condition
Soil Strength (CI)
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
Depth Inches
High Measured Cone Index
Low Measured Cone Index
Predicted Cone Index

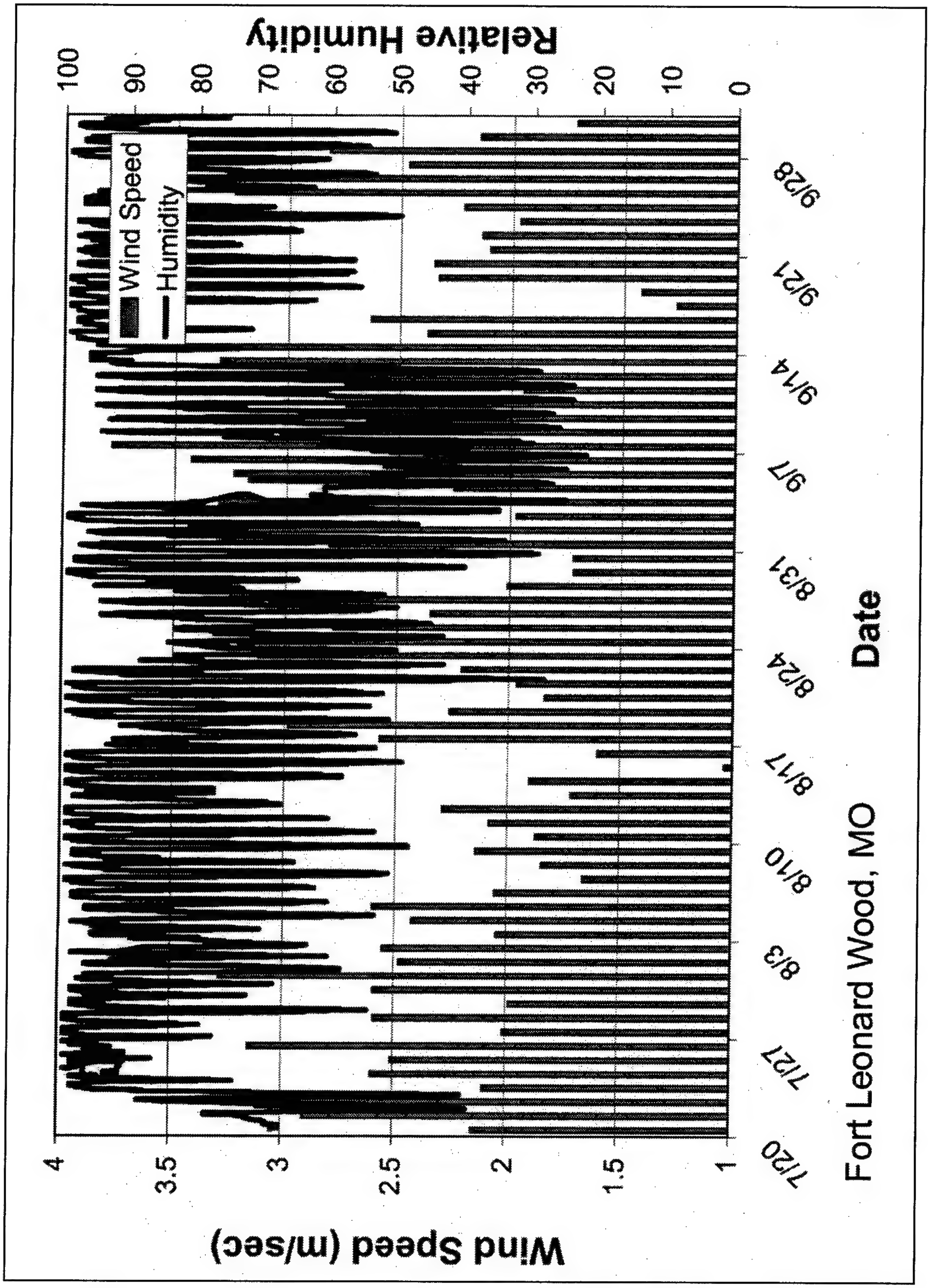
PLATE 4

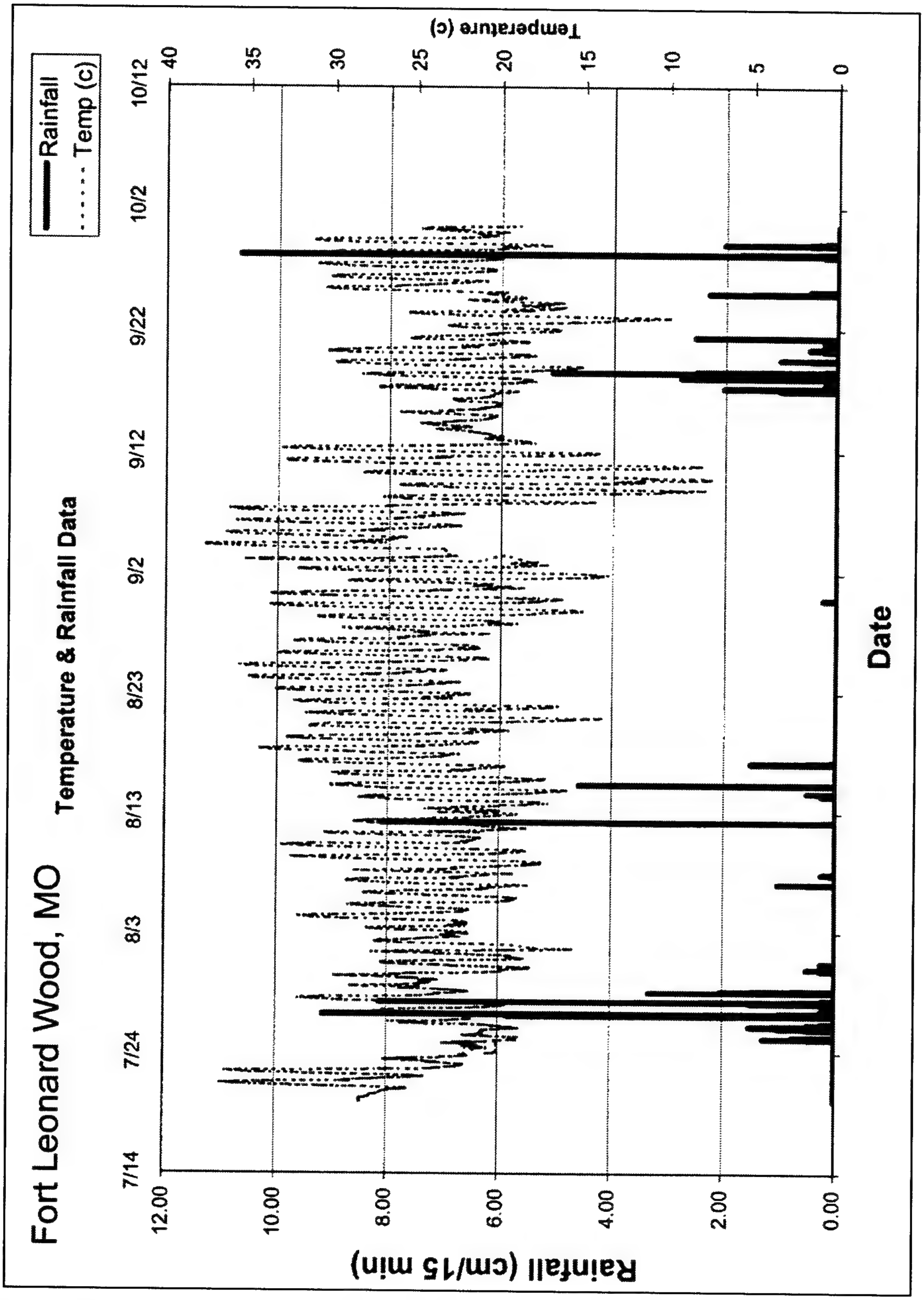

Poor House Property
Vicksburg, MS
Flooded Site
Soil Strength (CI)
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
Depth Inches
High Cone Index
Low Cone Index
Predicted Cone Index



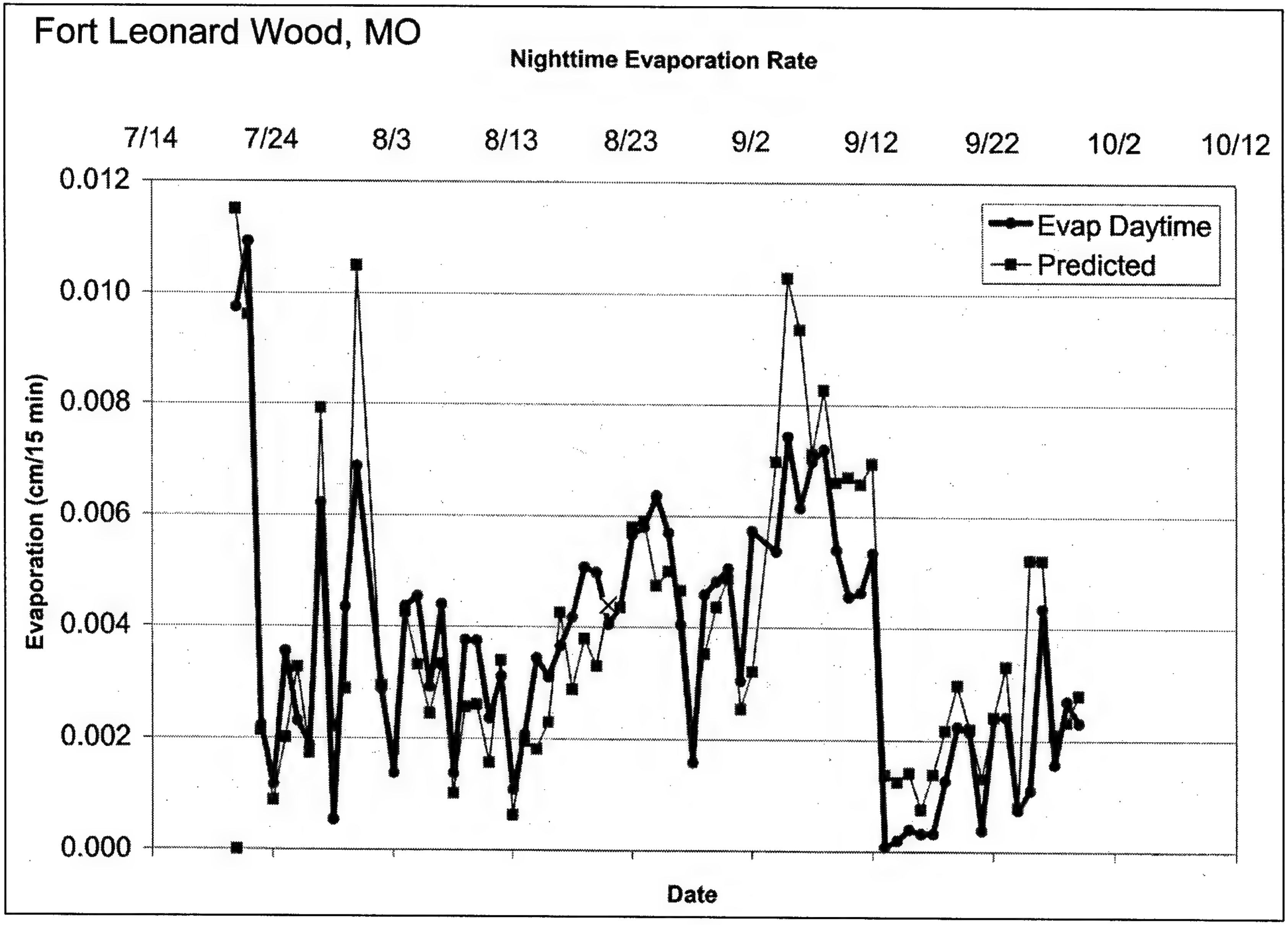
Poor House Property
Vicksburg, MS
Flooded Area
Soil Strength Profile
Left Side
Predicted Cone Index
Low Measured Cone Index
High Measured Cone Index
800
600
400
200
0
Soil Strength (CI)
0
5
10
15
Depth Inches

PLATE 6


Fort Leonard Wood, MO
Wind Speed (m/sec)
4
3.5
3
2.5
2
1.5
1
Relative Humidity
100
90
80
70
60
50
40
30
20
10
0
Wind Speed
Humidity
7/20
7/27
8/3
8/10
8/17
8/24
8/31
9/7
9/14
9/21
9/28
Date

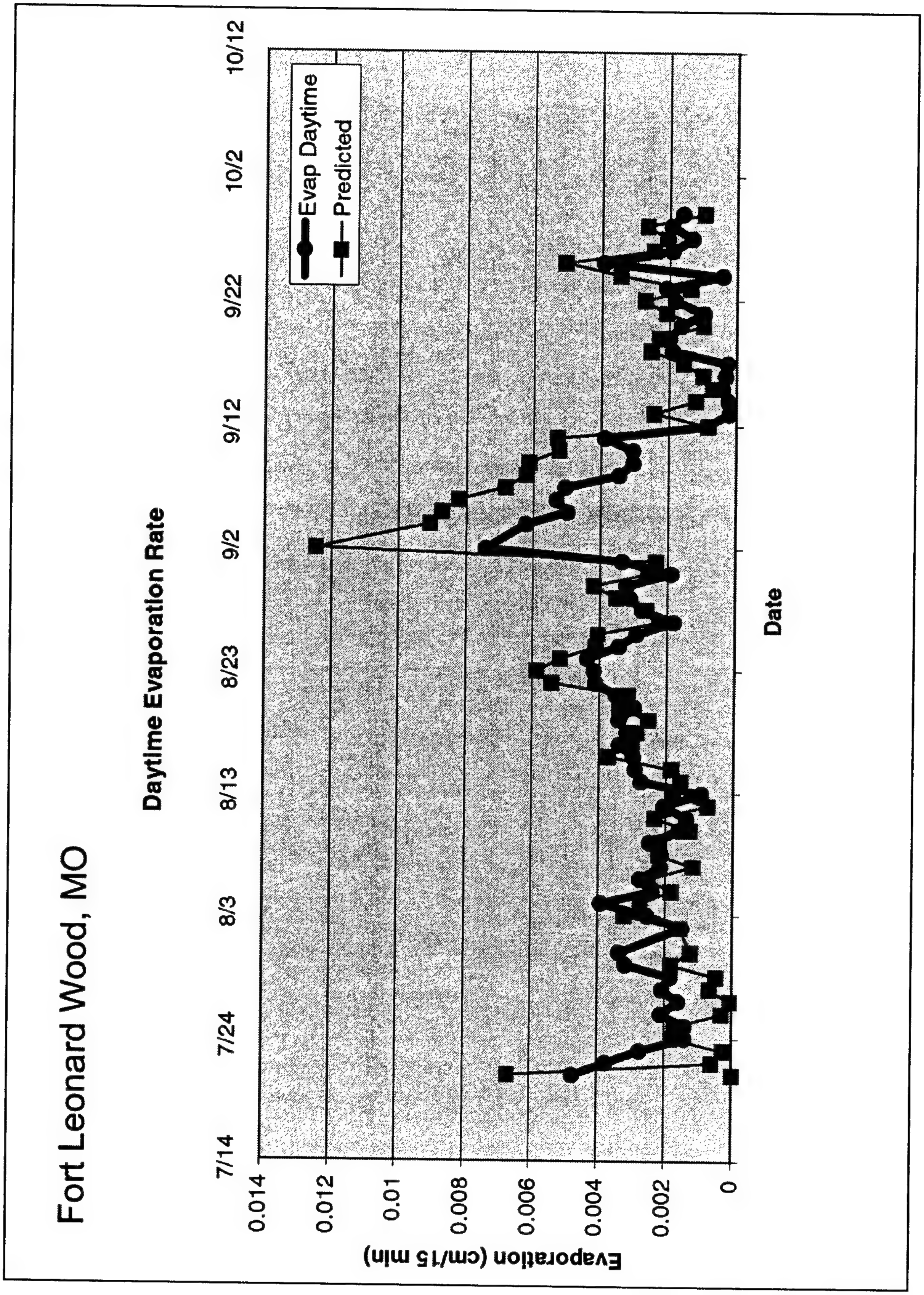


Fort Leonard Wood, MO
Temperature & Rainfall Data
Rainfall
Temp (c)
Rainfall (cm/15 min)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Temperature (c)
40
35
30
25
20
15
10
5
0
7/14
7/24
8/3
8/13
8/23
9/2
9/12
9/22
10/2
10/12
Date



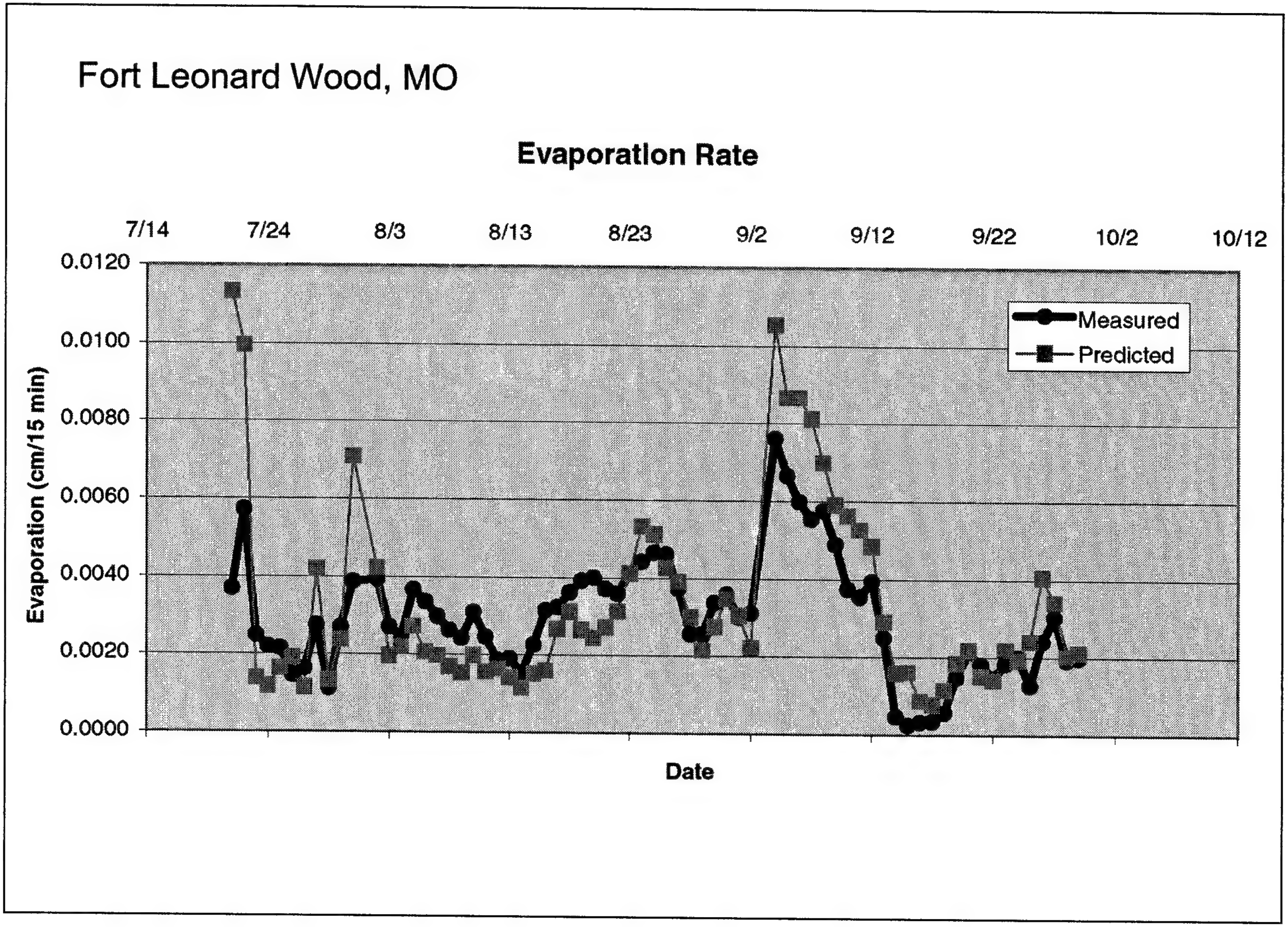
Fort Leonard Wood, MO
Nighttime Evaporation Rate
7/14
7/24
8/3
8/13
8/23
9/2
9/12
9/22
10/2
10/12
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Evaporation (cm/15 min)
Evap Daytime
Predicted
Date

PLATE 9



Fort Leonard Wood, MO
Daytime Evaporation Rate
Evap Daytime
Predicted
Evaporation (cm/15 min)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
7/14
7/24
8/3
8/13
8/23
9/2
9/12
9/22
10/2
10/12
Date

PLATE 10



Fort Leonard Wood, MO
Evaporation Rate
7/14
7/24
8/3
8/13
8/23
9/2
9/12
9/22
10/2
10/12
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
Evaporation (cm/15 min)
Measured
Predicted
Date

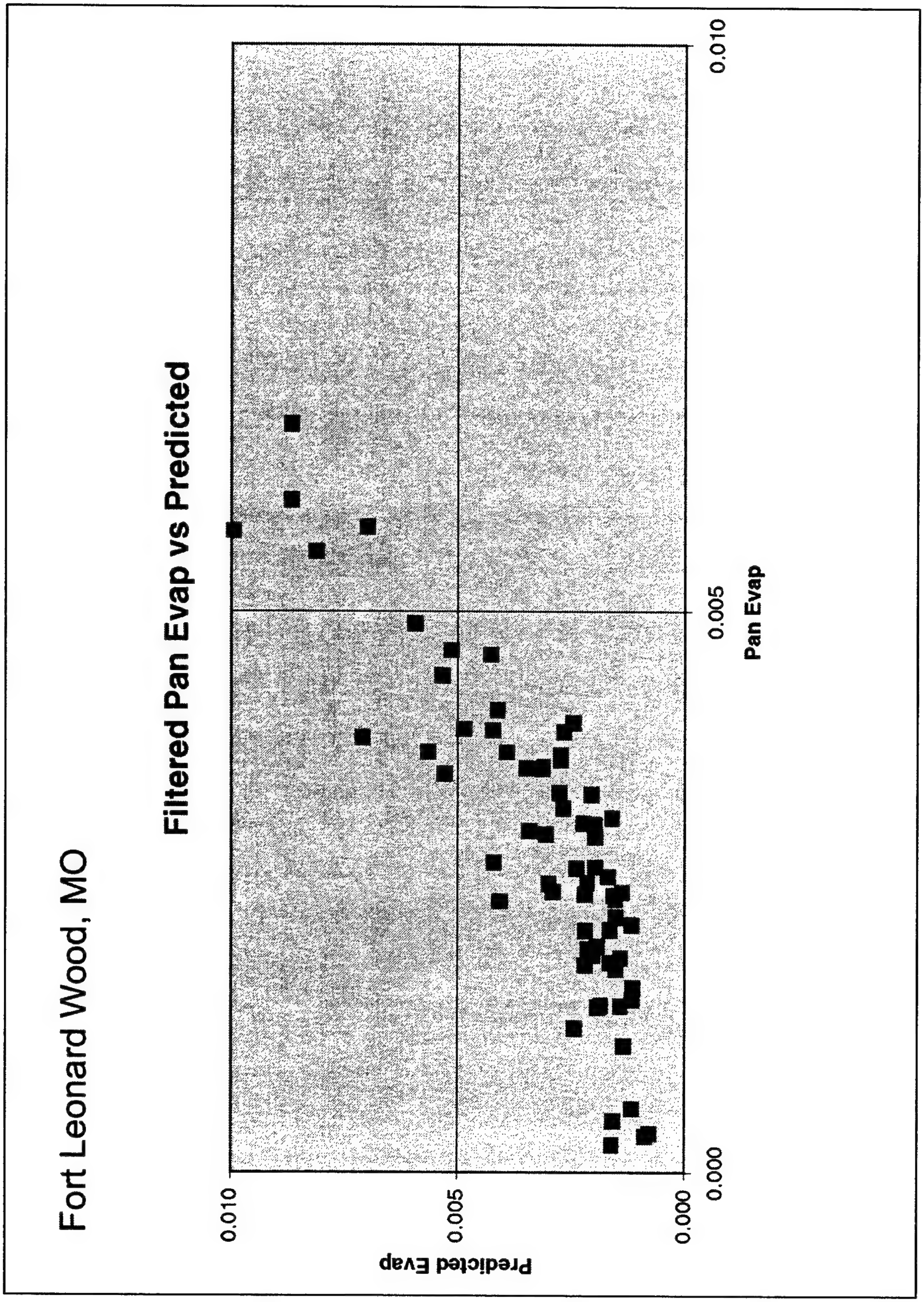
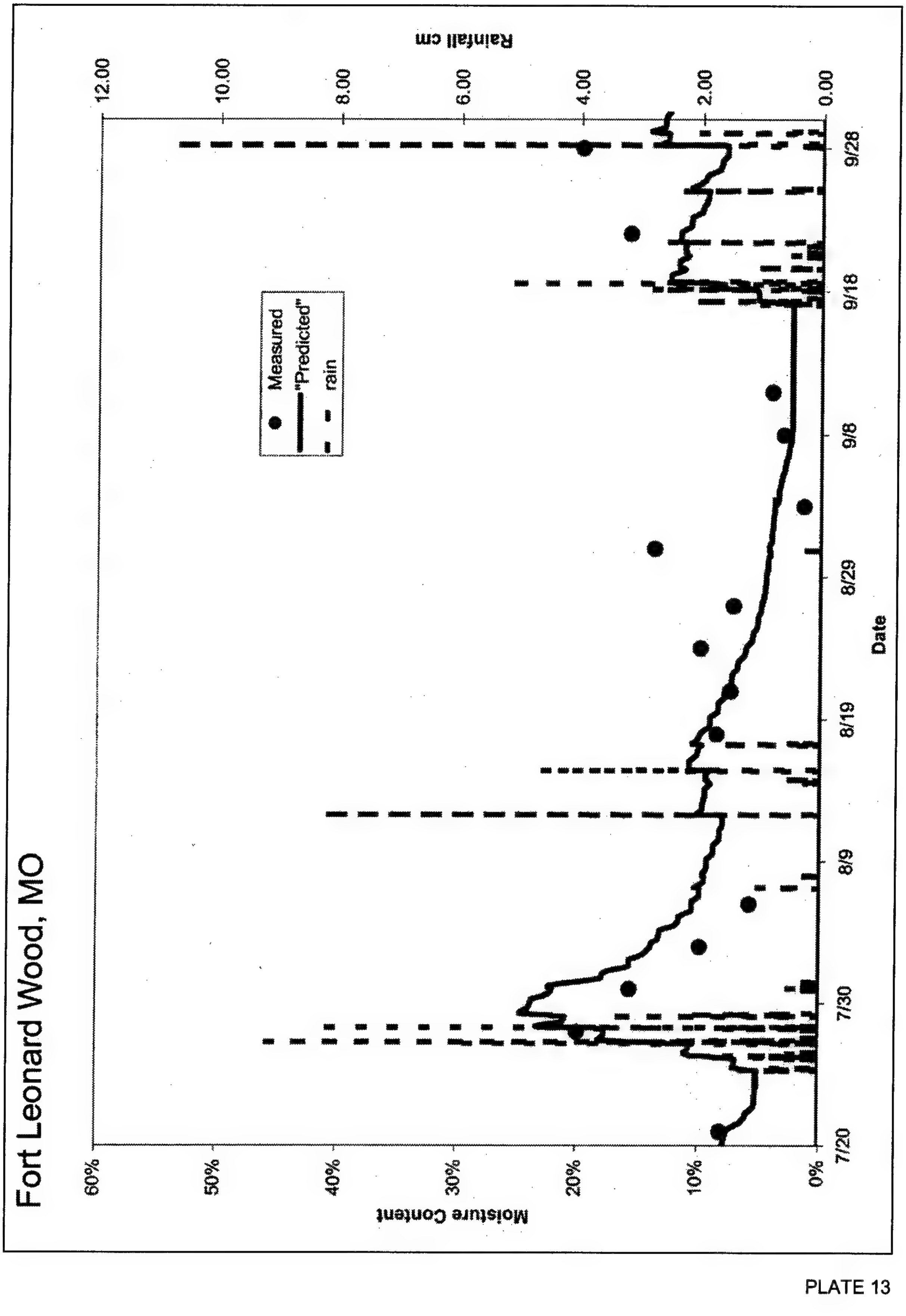
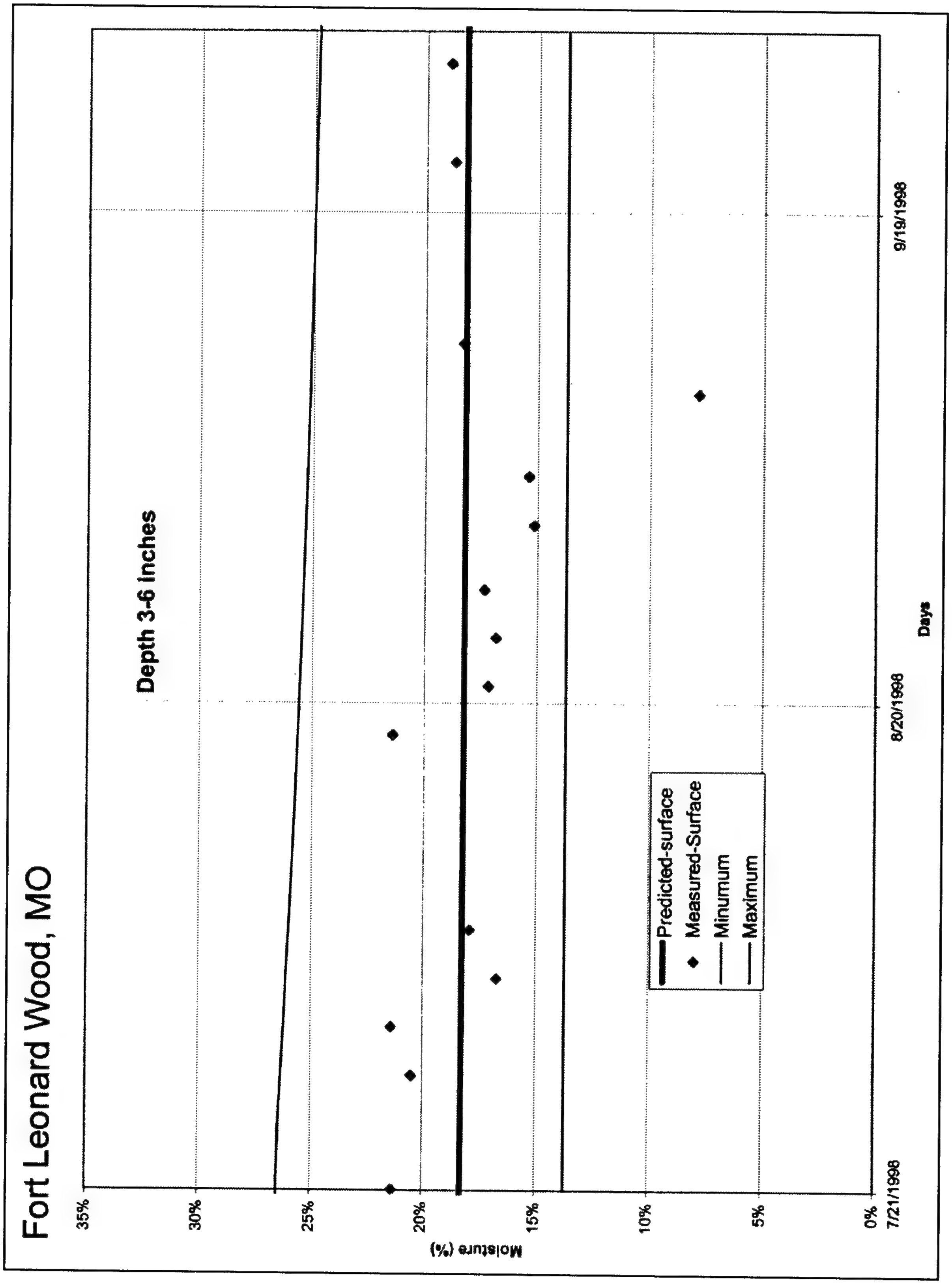

Fort Leonard Wood, MO
Filtered Pan Evap vs Predicted
0.010
0.005
0.000
Predicted Evap
0.000
0.005
0.010
Pan Evap

PLATE 12

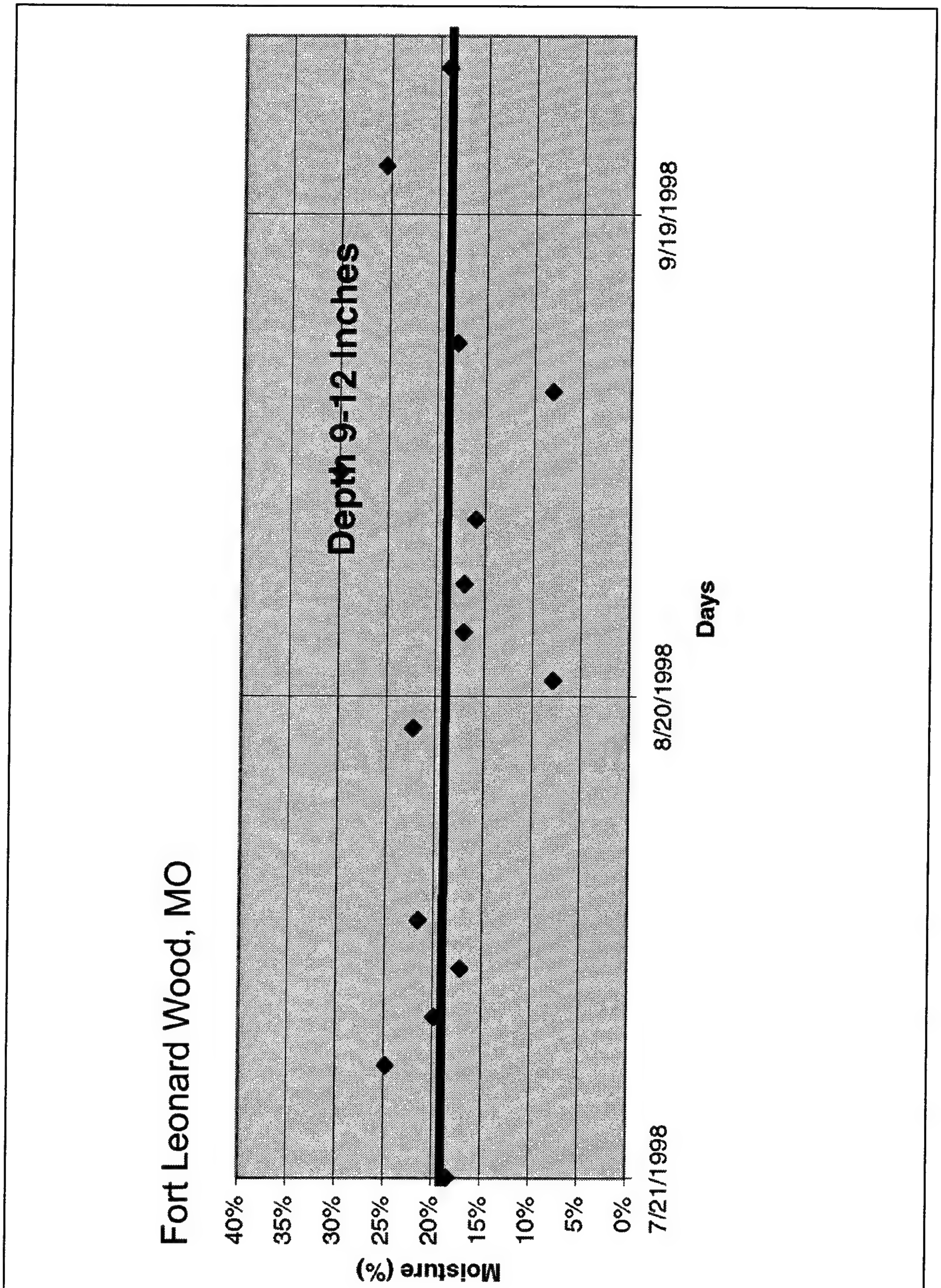


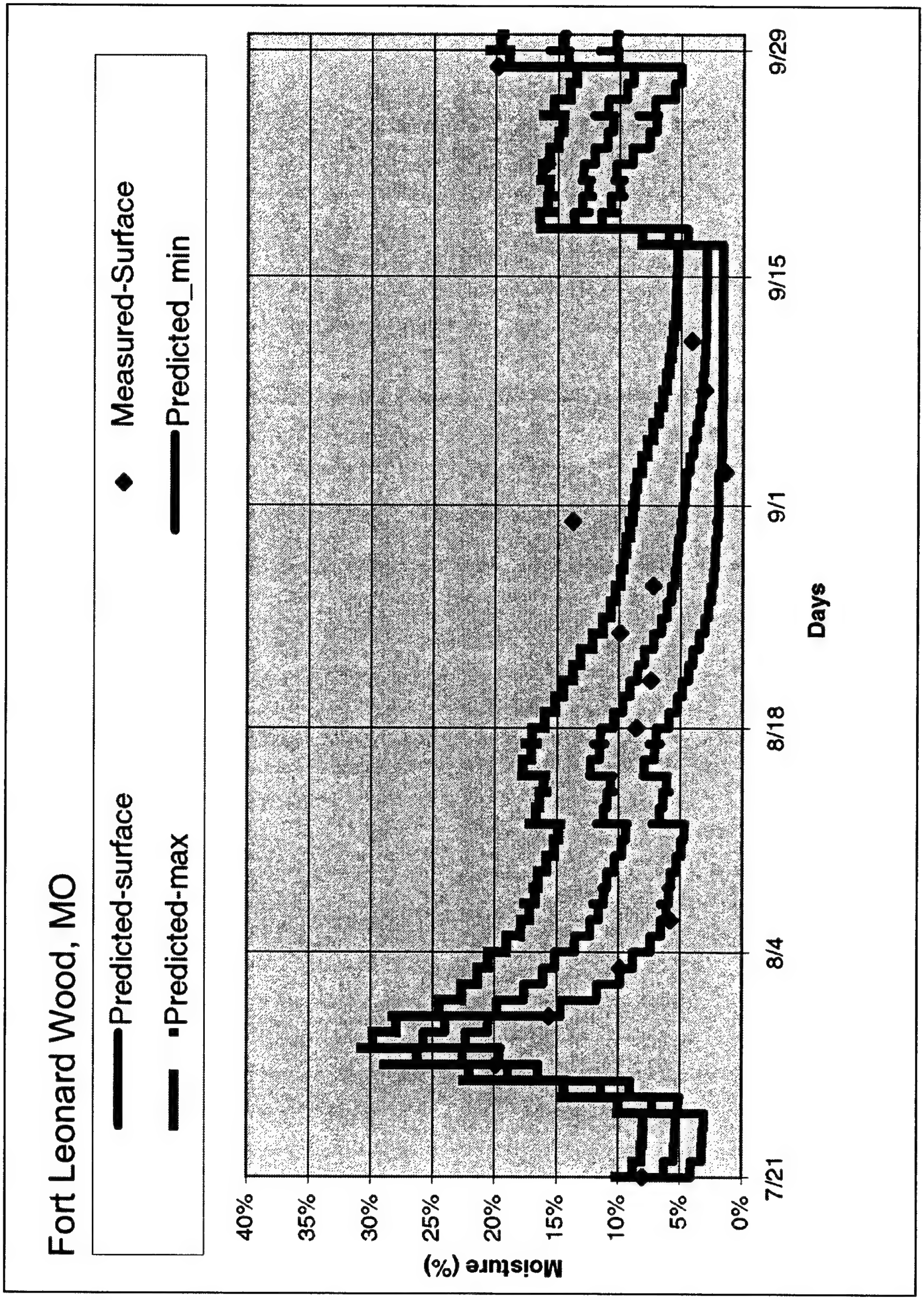
Fort Leonard Wood, MO
Moisture Content
0%
10%
20%
30%
40%
50%
60%
Rainfall cm
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Date
7/20
7/30
8/9
8/19
8/29
9/8
9/18
9/28
Measured
"Predicted"
rain

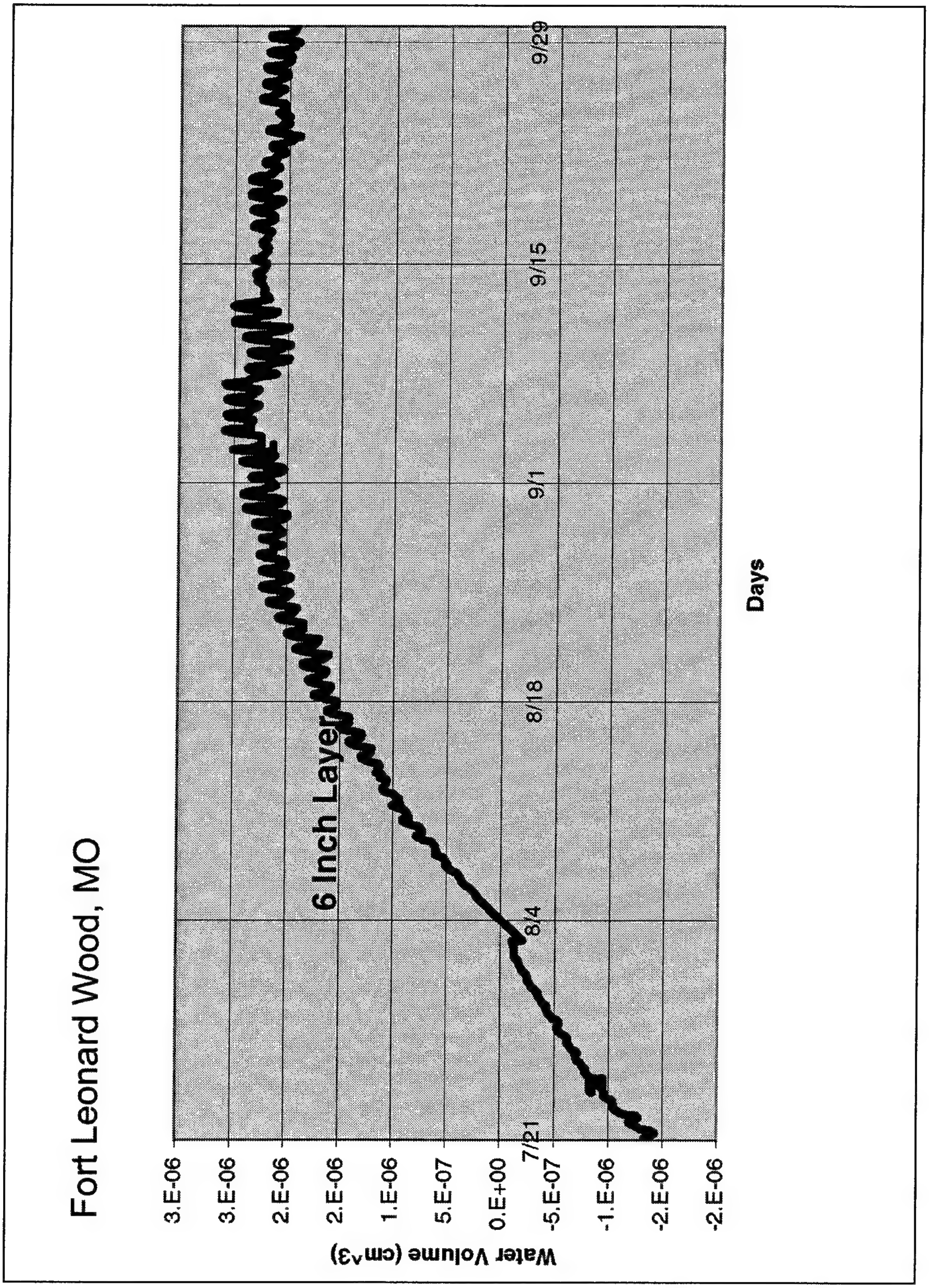


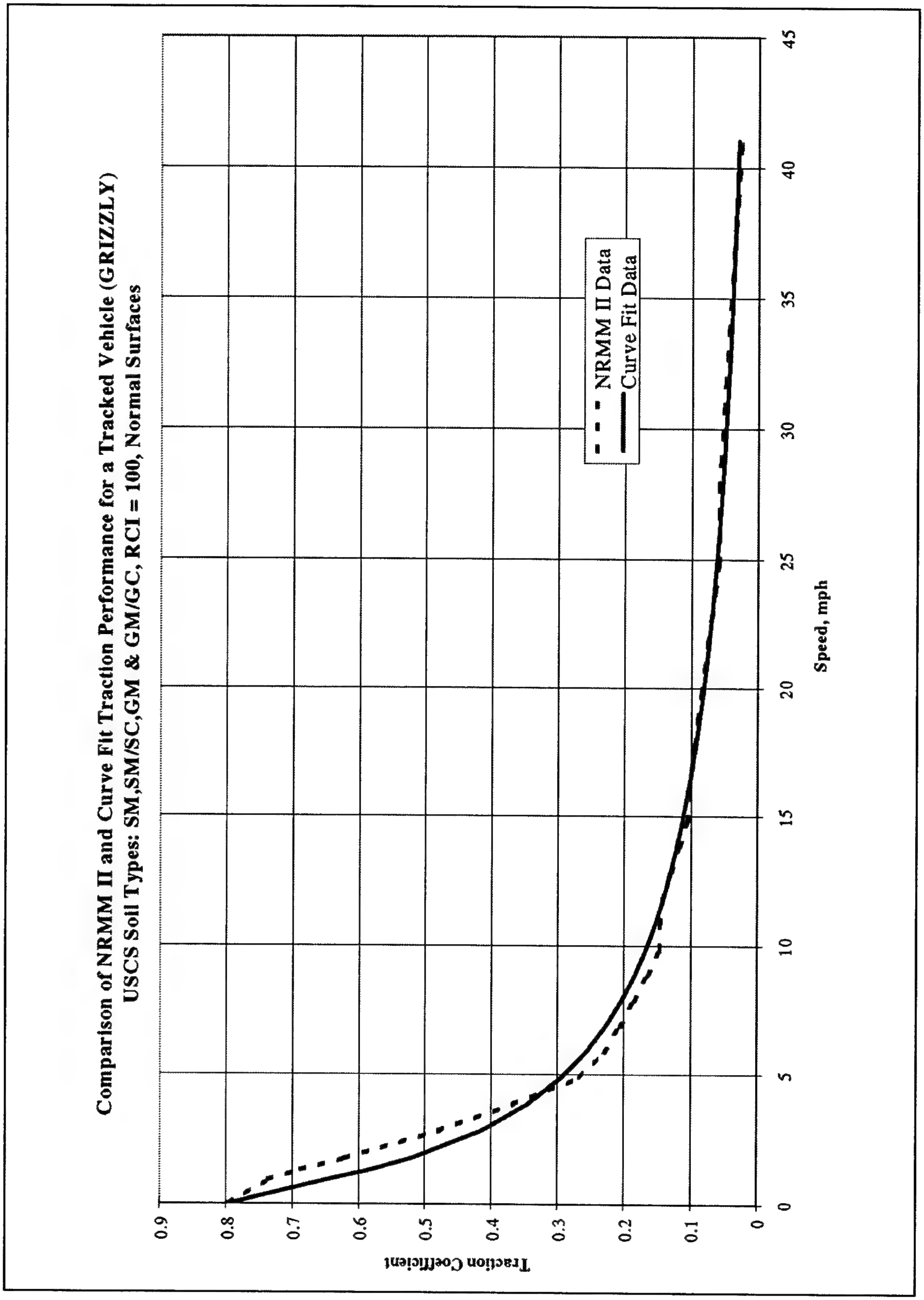
Fort Leonard Wood, MO
Depth 3-6 Inches
Moisture (%)
35%
30%
25%
20%
15%
10%
5%
0%
7/21/1998
8/20/1998
9/19/1998
Days
Predicted-surface
Measured-Surface
Minumum
Maximum

PLATE 14

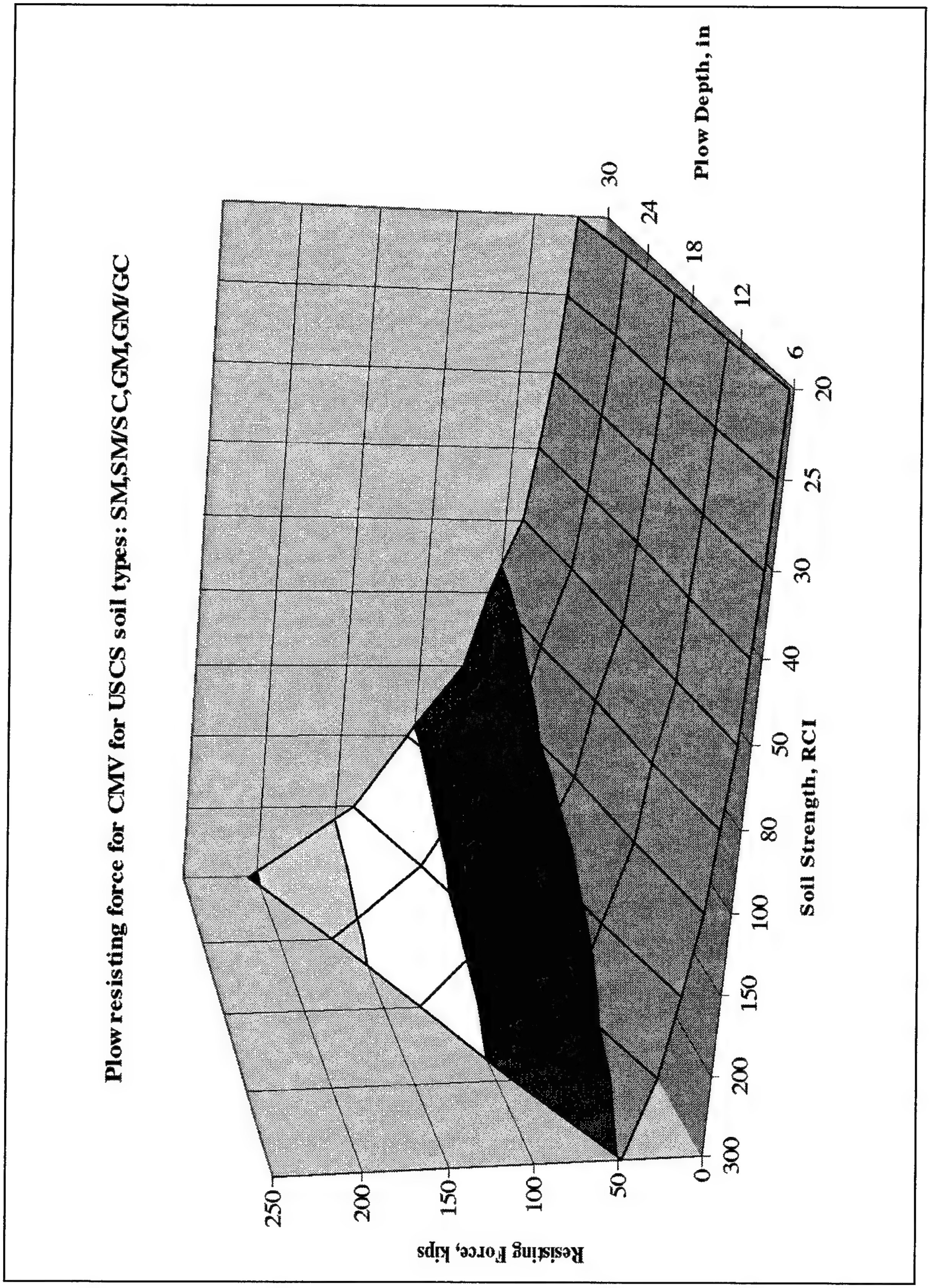

Fort Leonard Wood, MO
Depth 9-12 Inches
Moisture (%)
40%
35%
30%
25%
20%
15%
10%
5%
0%
7/21/1998
8/20/1998
9/19/1998
Days


Fort Leonard Wood, MO
Predicted-surface
Measured-Surface
Predicted-max
Predicted_min
Moisture (%)
40%
35%
30%
25%
20%
15%
10%
5%
0%
7/21
8/4
8/18
9/1
9/15
9/29
Days


Fort Leonard Wood, MO
6 Inch Layer
Water Volume (cm^3)
3.E-06
3.E-06
2.E-06
2.E-06
1.E-06
5.E-07
0.E+00
-5.E-07
-1.E-06
-2.E-06
-2.E-06
7/21
8/4
8/18
9/1
9/15
9/29
Days

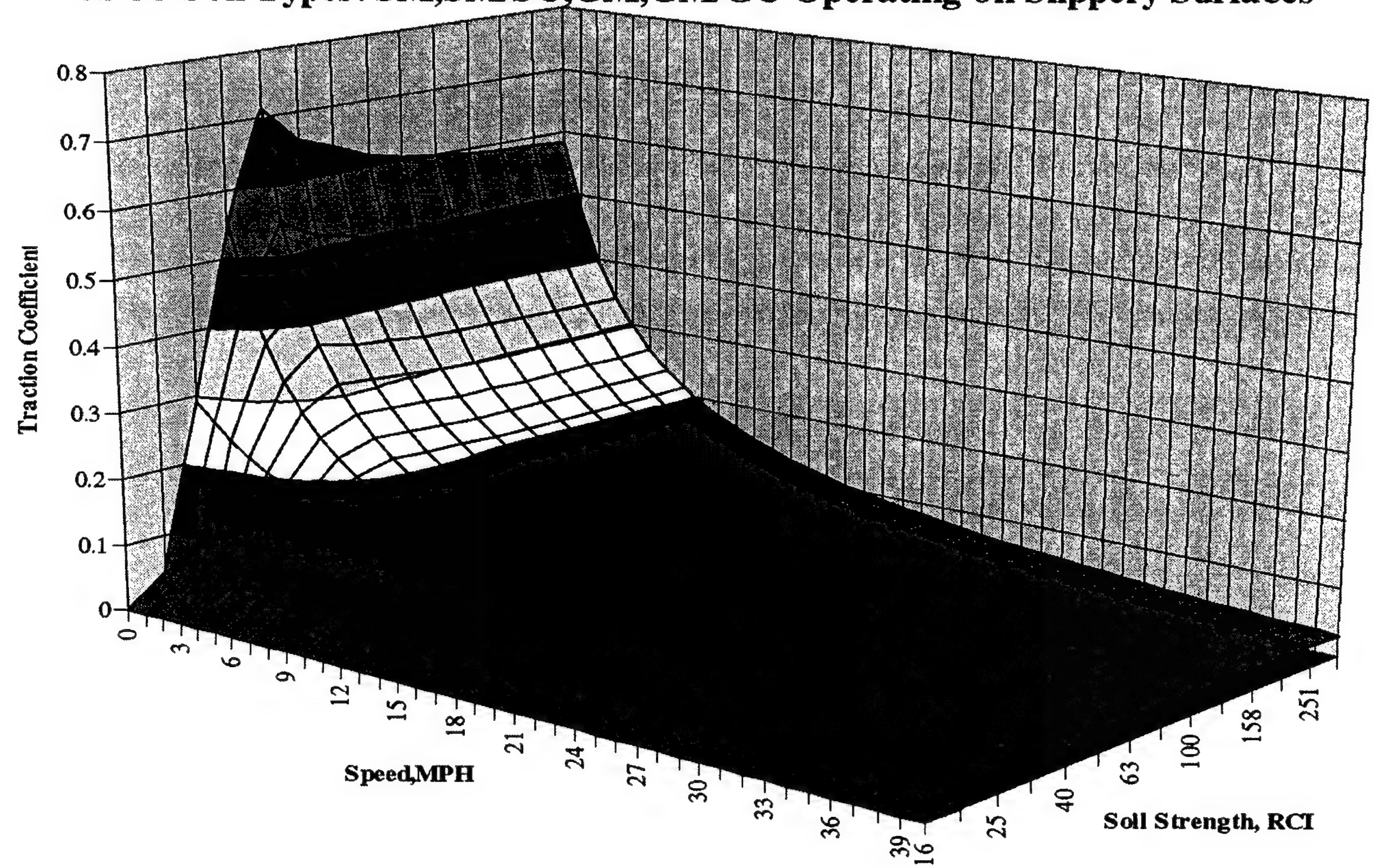


Comparison of NRMM II and Curve Fit Traction Performance for a Tracked Vehicle (GRIZZLY)
USCS Soil Types: SM,SM/SC,GM & GM/GC, RCI = 100, Normal Surfaces
NRMM II Data
Curve Fit Data
Traction Coefficient
Speed, mph
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
5
10
15
20
25
30
35
40
45



Plow resisting force for CMV for USCS soil types: SM,SM/SC,GM,GM/GC
Resisting Force, kips
250
200
150
100
50
0
300
200
150
100
80
50
40
30
25
20
Soil Strength, RCI
6
12
18
24
30
Plow Depth, in

Traction Performance of a Tracked Vehicle (GRIZZLY)
USCS Soil Types: SM,SM/SC,GM,GM/GC Operating on Slippery Surfaces



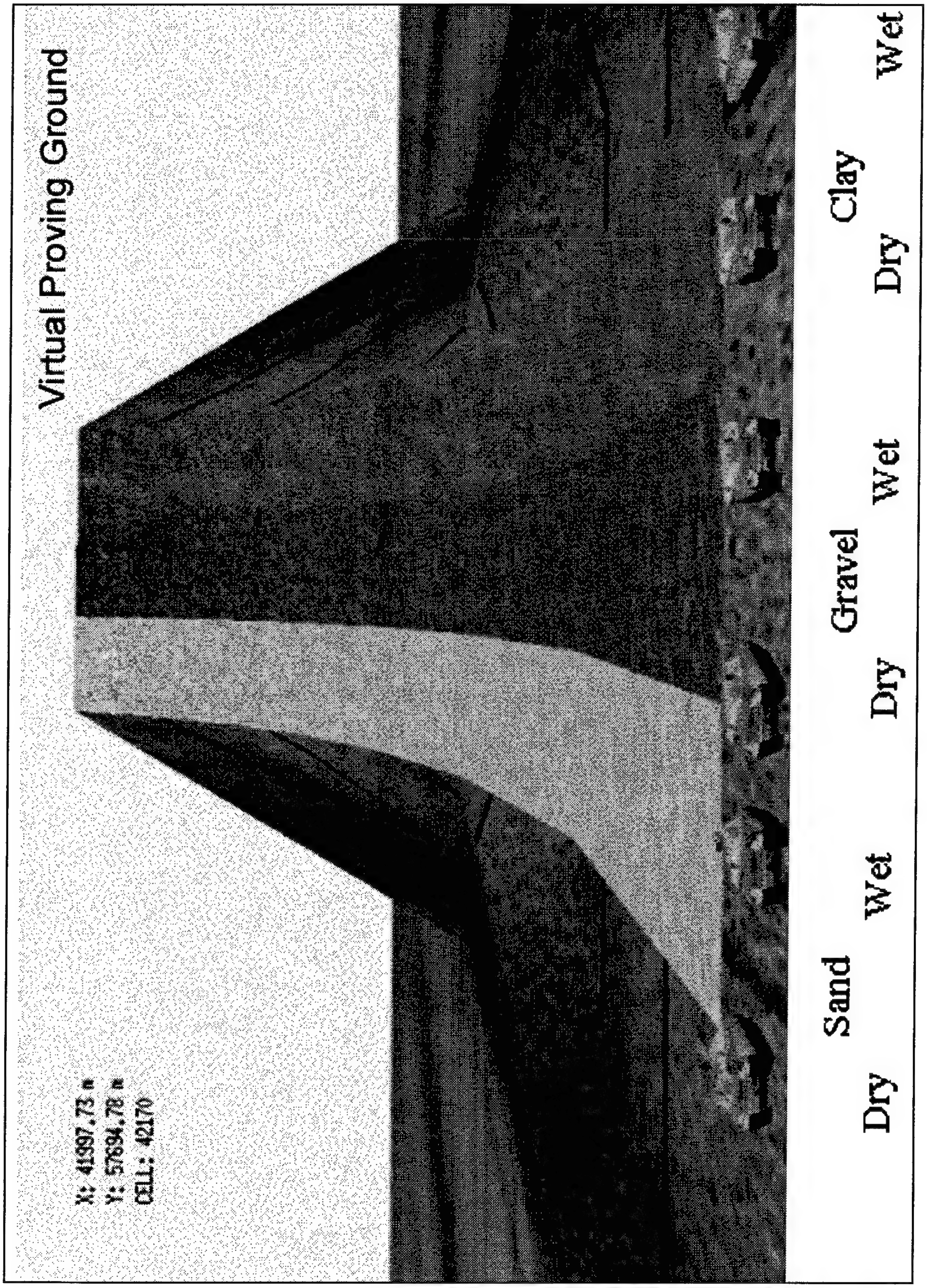

Virtual Proving Ground
X: 41997.73 m
Y: 57694.78 m
CELL: 42170
Dry Sand Wet
Dry Gravel Wet
Dry Clay Wet

PLATE 21

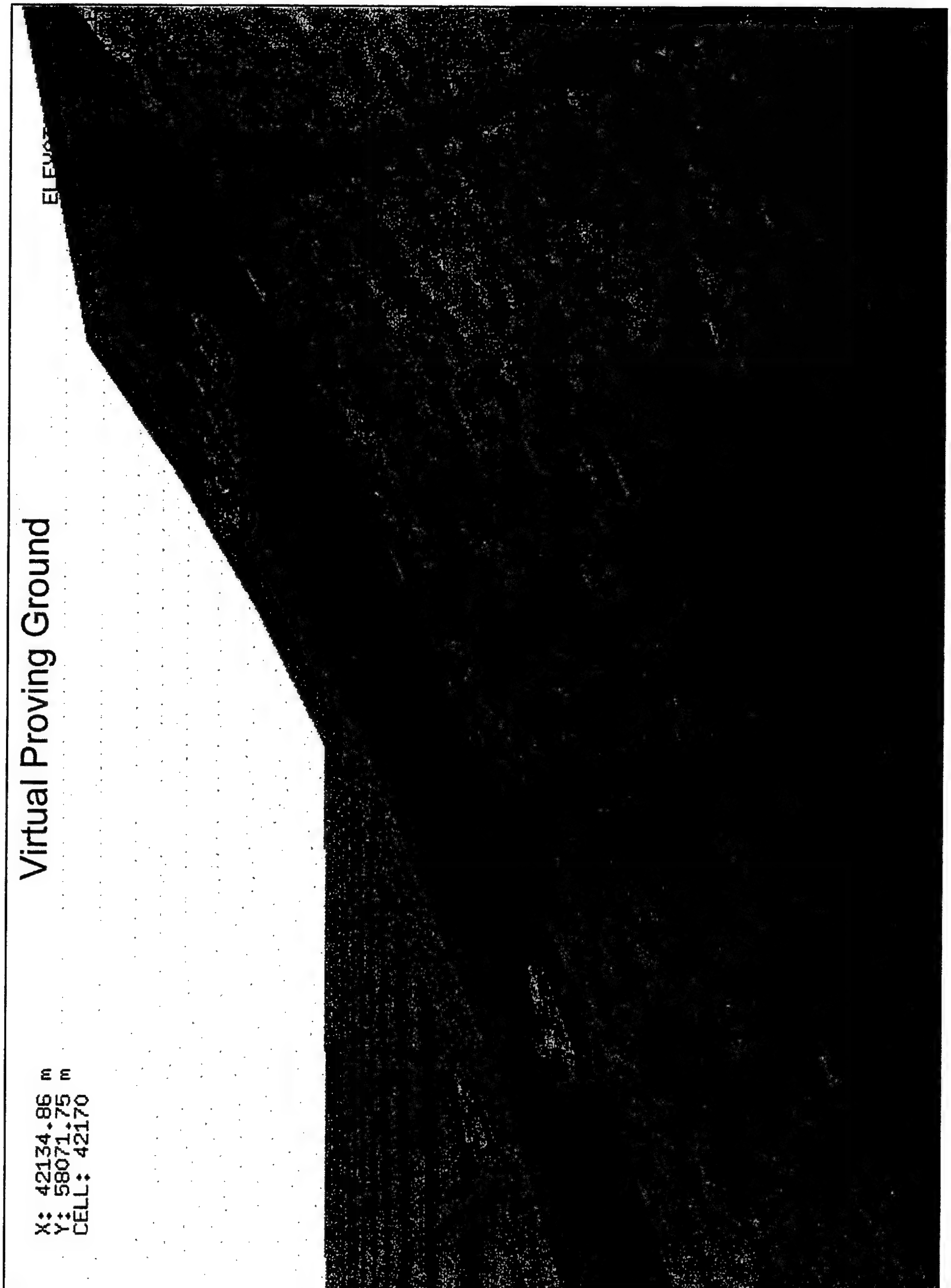


PLATE 22

Appendix A
SOFT API for SAF model

```
C  SMSP (SOFT) API specification
C
C     Richard Ahlvin, USAEWES ERDC
C  08/20/98   first draft
C  08/21/98   second draft
C*******************************************************************
****
C
      FUNCTION  SMSPSOFT( SOILTYPE, VEGETATN, SLOPE,
     +                    PRECPCUR, SURFTEMP, WINDVEL,
     +                    PRECPSUM, LAPSESEC, SATURATN,
     +                    MOIST_3,  MOIST_12, CINDX_3, CINDX_12)
C
C 18 Sep 98    Beta release
C
C*******************************************************************
****
C  --FUNCTION          SMSPSOFT
C
C  --DESCRIPTION
C  The function accepts  a set of climatic input and terrain
C  data to make the prediction of soil strength and moisture.
C  The simplified Soil Moisture Strength Prediction Model (II)
C  is used in the computation. MOIST_3 and MOIST_12 are taken
C  as input arguments describing previous moisture conditions
C  and then overwritten as output arguments reporting the new
C  moisture values under the current climatic condition. Soil
C  cone indices  CINDX_3 and CINDX_12 are also calculated and
C  returned by the function accordingly.
C
C  The function also checks the validity of input parameters.
C  It will report errors (by returning 0) if there is invalid
C  input data.
C
C   --INPUT PARAMETERS
C        SOILTYPE:      Soil type
C                       0 - 18 (USCS types)
C               Encoded as per ITD as follows:
C                0 = UNKNOWN     7 = SM         14 = OH
C                1 = GW          8 = SC         15 = PT
C                2 = GP          9 = ML         16 = Not Used
C                3 = GM         10 = CL         17 = Not Used
C                4 = GC         11 = OL         18 = Not Used
C                5 = SW         12 = CH
C                6 = SP         13 = MH
C  Note: SOILTYPE out of range [1..15} produce an error return
C  VEGETATN:  Surface vegetation cover code (See Note:1)
C                       0    (BARE)
```

```
C                         1    (GRASS)
C                         2    (FOREST)
C  SLOPE:  Surface slope code (45 degree slope == 100%)
C                         0    [ 0% :  2%)
C                         1    [ 2% :  5%)
C                         2    [ 5% : 10%)
C                         3    [11% : 20%)
C                         4    [20% : 100%]
C  PRECPCUR:  Current precipitation rate in mm/hour (See Note:1)
C  SURFTEMP:  Terrain surface temperature (in Celsius) (See
   Note:1)
C  WINDVEL:  Surface wind velocity (x, y), meter/second (See
   Note:1)
C  PRECPSUM:  Total precipitation (mm) in the last hour (See
   Note:2)
C  PRECPLPS:  Time lapse (seconds) since last precipitation.
   (Note:1)
C  SATURATN:  Sub-surface soil saturation (See Note:1 & 4)
C                         0     (no rain in past hour)
C                         1     (rain in previous half hour)
C                         2     (0.8 mm/min in past 10 minutes)
C                         3     (4.0 mm/min in past 10 minutes)
C                         4     ( >4 mm/min in past 10 minutes)
C
C  --INPUT/OUTPUT PARAMETERS
C  MOIST_3:  Soil moisture of surface layer in % by weight
   (Note:3)
C  MOIST_12:  Soil moisture (0-12") in % by weight
C
C  --OUTPUT PARAMETERS
C  CINDX_3:  Coin index of surface layer in PSI. (Note:3)
C  CINDX_12:  Coin index (0-12") in PSI.
C
C
C  --RETURN:
C  The function returns 1 if the computation is successful.
C  0 is returned if any error occurs.
C
C Notes:
C  (1).Current system does not use VEGETATION, PRECPCUR, SURFTEMP,
C  WINDVEL, PRECPLPS, or SATURATN
C  (2).Since no explicit time period is given, and rain
   (PRECPSUM)is being
C  supplied as total for the past hour, the assumption is made
C  that the time period is one hour.
C  (3)  Since no separate surface layer data is being supplied,
C  the 0"-3" soil layer is assumed to be the surface layer.
C  (4)  This appears to be a time lapse code rather than a
C  saturation.
C*****************************************************************
C
C Internal:
C     EVAPORATION   Function to obtain evaporation amount [in]
C     DELTAT        Time period [ 3600. sec]
C     DEPTH(0:1)    Depth of surface, and soil layer [in]
C     I             Loop index for layers
C     ISOIL         SMSP/SOFT Soil type code as follows:
C                   1 =  SW     6 =  CL     11 =  OL
C                   2 =  SP     7 =  ML     12 =  OH
C                   3 =  SM     8 = CLML    13 =  GM
C                   4 =  SC     9 =  CH     14 =  GC
C                   5 = SMSC   10 =  MH
C   IXLST  Function to translate input soil code to SMSP/SOFT code
C   MOIST(0:1)    Moisture content of surface & soil layer [%]
C   NLAYERS       Number of soil layers [1]
C   RAININ        Total rainfall for time period [in]
C   RUNOFF        Amount of runoff [in]
```

```
C   SLOPECLASS(0:5)  Lower (i-1) & upper (i) bounds of each slope-
C              class range [%]
C  SLOPEVAL       Value of slope for given slope class [%]
C  SMSPSOFT_RCI  Function to convert moisture content to soil
   strength
C  SUM       Sum of moisture content for each layer
C  TANSLOPE       Tangent of slope
C
C
      IMPLICIT NONE
      INTEGER   SMSPSOFT
      INTEGER   LAPSESEC, SATURATN, SLOPE, SOILTYPE, VEGETATN
      REAL      CINDX_3, CINDX_12, MOIST_3,  MOIST_12, PRECPCUR,
      &          PRECPSUM, SURFTEMP, WINDVEL(2)
C
C     Number of soil layers
      INTEGER NLAYERS
      PARAMETER ( NLAYERS = 1 )
C     Conversion factor for mm to inches
      REAL XMM2IN
      PARAMETER ( XMM2IN = 1. / 25.4 )

      INTEGER I, ISOIL, ISTAT, IXLST(15), SMSPSOFT_UPD
      EXTERNAL SMSPSOFT_UPD
      REAL EVAPORATION, DELTAT, DEPTH(0:NLAYERS), MOIST(0:NLAYERS),
      &     RAININ, RUNOFF, SLOPECLASS(0:5), SLOPEVAL,
      &     SMSPSOFT_RCI, SUM, TANSLOPE
      EXTERNAL EVAPORATION, SMSPSOFT_RCI
C
C      Time period:
       PARAMETER ( DELTAT = 3600. )
C      Layer depths
       DATA DEPTH / 1.0, 12.0 /
C
C      Translation from input (ITD) soil type codes to internal
C      (SMSPSOFT) soil type codes:
C             GW  GP  GM  GC  SW  SP  SM  SC  ML  CL
       DATA IXLST /  1,  2, 13, 14,  1,  2,  3,  4,  7,  6,
C             OL  CH  MH  OH  Pt
      &             11,  9, 10, 12,  0 /
C
C      Class range values for input slope (%)
       DATA SLOPECLASS / 0.0, 2.0, 5.0, 10.0, 20.0, 100. /
C
C      Check input arguments
       IF( SOILTYPE .LT. 1 .OR. SOILTYPE .GT. 14 .OR.
      &    SLOPE .LT. 0 .OR. SLOPE . GT. 4 )THEN
C     Set error return status
         SMSPSOFT = 0
       ELSE
C
C     Translate input soil type to internal SMSPSOFT code:
         ISOIL = IXLST(SOILTYPE)
         MOIST(0) = MOIST_3
         DO I=1, NLAYERS
           MOIST(I) = MOIST_12
         END DO
C     Rain fall amout for 1-hour in inches:
         RAININ = PRECPSUM * XMM2IN
C        Use mid-point slope class value for slope
       SLOPEVAL = ( SLOPECLASS(SLOPE) + SLOPECLASS(SLOPE+1) ) / 2.0
C        Tangent of slope
         TANSLOPE = SLOPEVAL / 100.
         ISTAT = SMSPSOFT_UPD( DELTAT, DEPTH,
     &           EVAPORATION( DELTAT, ISOIL, MOIST, DEPTH ),
     &            ISOIL, MOIST, NLAYERS, RAININ, RUNOFF, TANSLOPE )
         IF( ISTAT .EQ. 0 )THEN
```

```
              MOIST_3   = MOIST(0)
              SUM = 0.
              DO I=1, NLAYERS
                SUM = SUM + MOIST(I)
              END DO
              MOIST_12 = SUM / NLAYERS
              CINDX_3  = SMSPSOFT_RCI( ISOIL, MOIST_3 )
              CINDX_12 = SMSPSOFT_RCI( ISOIL, MOIST_12 )
C       Set successful return status
              SMSPSOFT = 1
          ELSE
C       Set error return status
            WRITE(*,*)'SMSPSOFT_UPD status=',ISTAT
            SMSPSOFT = 0
          END IF
        END IF
        RETURN
        END
C SMSPSOFT_UPD SMSP II with Surface layer
C*****************************************
C                *
C S M S P S O F T _ U P D *
C                *
C**************************
        FUNCTION SMSPSOFT_UPD( TIME, DEPTH, EVAPRATE, ISOIL,
     &                         MOIST, NLAYERS, RAIN, RUNOFF, SLOPE )
C
C 21 Sep 98    Initial edit RBA-GL
C
C  This routine updates the soil moisture in a multi-layered
C  system for one time period as a result of given rainfall for
C  the period.
C
C Inputs:
C     TIME      {r}  Time interval [sec]
C  DEPTH(0:n){r} Depth to bottom of each of n soil layers from the
C               Surface (layer #0 is the surface) [in]
C     EVAPRATE {r}  Surface evaporation [in]
C     ISOIL    {i}  Soil type code as follows:
C                    1 =  SW    6 =  CL    11 =  OL
C                    2 =  SP    7 =  ML    12 =  OH
C                    3 =  SM    8 = CLML   13 =  GM
C                    4 =  SC    9 =  CH    14 =  GC
C                    5 = SMSC  10 =  MH
C  MOIST(0:n){r} Moisture content (percent by weight) of each of n
C    soil layers (layer #0 is the surface) [%]
C  NLAYERS {i} Number of soil layers, NOT counting the surface.
    [n]
C     SLOPE    {r}  Terrain slope [tan]
C     RAIN     {r}  Total rainfall amount for time period [in]
C   Common /SMSPSOFTDIAG/
C     DIAG     {l}  Internal diagnostics printout flag:
C             .FALSE. (default) do not poduce internal diagnostics
C              .TRUE. internal diagnostics will be written to
C              standard (system) output
C
C Outputs:
C     RUNOFF   {r}  Amount of runoff [in]
C     SMSPSOFT_UPD {i}   Return code as follows:
C              0 = Successful return
C              1 = Soil type (ISOIL) out of range
C              2 = NLAYERS out of range (1..MLAYERS)
C              3 = Zero or negative soil layer (data for DEPTH not
C                  in ascending order)
C  MOIST(0:n){r} Moisture content (percent by weight) of each of
C    NLAYERS soil layers as a result of the given rainfall for the
C              period [%]
```

```
C Internal:
C     DELTAVW        Maximum amount of water allowed into surface
C     EVAPCM         Evaporation amount [cm]
C     I              Layer index
C  KBAR(0:NLAYERS)    Intermediate variable for layer flow rate
    computation
C     MC        Moisture content argument for ASF
C     RAINCM         Rainfgall amount [cm]
C     RUNOFFCM       Amount of runoff [cm]
C     S            Intermediate variable for surface layer flow rate
C               computation
C     TL        Thickness of layer argument for ASF
C     VC        Volume of water (column) argument to ASF
C     VIN       Water input to surface layer
C   VMAX  Maximum amount of water allowed for soil (field maximum)
C   VMIN  Minimum amount of water allowed for soil (field minimum)
C     WATER          Density of water [lb/ft^3]
C     XMC2V          Function to convert moisture content to volume
C   XV2MC  Function to convert volume (column) to moisture content
C
C   Common /SMSPSOFTDATA/ Internal common data
C  DELTAV(0:NLAYERS) Flow volume OUT (neg=out) at bottom of each
    layer [cm]
C     K(0:NLAYERS)  Relative permeability, each layer
C     PSI(0:NLAYERS)      Bubbling pressure, each layer
C    Q(0:NLAYER)   Flow rate OUT (neg=out) at bottom of each layer
C     T(0:NLAYER)   Thickness of each layer [cm]
C     V(0:NLAYERS)  Water volume [cm]
C  W(0:NLAYERS)  Relative moisture content, each layer
    (0=min...1=max)
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C  BPSIMAX(MSOIL)  Y-intercept for Psi vs. W extension line, i.e.
C               Psi at W = 0. for each soil type
C     DENSITY(MSOIL)      Density of each soil type [lb/ft^3]
C     GAMMA(MSOIL)  Empiracle coefficient used to compute relative
C            permeability and bubbling pressure for each soil type
C    GS(MSOIL) Specific gravity of each soil type [same as density
C               in g/cm^3]
C     KS(MSOIL)    Saturated permeability (flow rate) for each soil
C               type [cm/sec]
C  MPSIMAX(MSOIL)  Slope of Psi vs. W relation at PSIMAX for each
    soil type
C     PSIS(MSOIL)    Bubbling pressure head at saturation for each
C               soil type [cm]
C     SOFTINIT       Flag to indicate SOFTINIT has been called
C  THETAR(MSOIL) Minimum moisture content by weight (field
    minimum) [%]
C  THETAS(MSOIL) Maximum moisture content by weight (field
    maximum) [%]
C  WPSIMAX(MSOIL) Value of W ( relative moisture content) at
    PSIMAX from
C               W vs. Psi relation for each soil type
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      LOGICAL DIAG
      COMMON /SMSPSOFTDIAG/DIAG
C
C     Arguments:
      INTEGER SMSPSOFT_UPD
      INTEGER ISOIL, NLAYERS
      REAL EVAPRATE, RAIN, RUNOFF, SLOPE, TIME
      REAL DEPTH(0:NLAYERS), MOIST(0:NLAYERS)
C     Internals:
      INTEGER I, ITER, NITER
      REAL ACCEPT, DELTAT, DELTAVW, DTNOM, EVAPCM, S, RAINCM,
     &     RUNOFFCM, VIN, VMAX, VMIN, MC, TL, VC, XMC2V, XV2MC
```

```
      REAL KBAR(0:MLAYERS)
      CHARACTER *5 ZSOIL(0:MSOIL)
      DATA DTNOM/60./
      DATA ZSOIL/'unkn)','SW)','SP)','SM)','SC)','SMSC)',
     &                  'CL)','ML)','CLML)','CH)','MH)',
     &                  'OL)','OH)','GM)','GC)'/
      XMC2V( MC, TL ) = MC * TL * DENSITY(ISOIL) / WATER
      XV2MC( VC , TL ) = VC / TL * WATER / DENSITY(ISOIL)
C
C     Diagnostic printout of inputs
      IF( DIAG )THEN
        I = MAX0( ISOIL, 0 )
        IF( I.GT.MSOIL )I = 0
   WRITE(*,601)DELTAT, EVAPRATE, EVAPRATE * 2.54, ISOIL, ZSOIL(I),
     &               SLOPE*100.0, RAIN, RAIN * 2.54
  601   FORMAT(' Routine SMSPSOFT_UPD inputs:'/
     &         3X,'Time interval',T30,F8.0,' (sec)'/
     &       3X,'Evaporation',T30,1PG15.6,' (in)',1PG15.6,' (cm)'/
     &         3X,'Soil type',T30,I8,' (',A/
     &         3X,'Slope',T30,F8.3,' (tan)'/
     &         3X,'Rain',T30,F8.2,' (in)',F8.2,' (cm)')
      END IF
C
      IF( .NOT. SOFTINIT ) CALL SMSPSOFT_INIT
      SMSPSOFT_UPD = 0
C
C *** Sanity checks
      IF( ISOIL .LT.1 .OR. ISOIL .GT. MSOIL )THEN
C       "ISOIL code out of range"
        SMSPSOFT_UPD = 1
        RETURN
      END IF
C
      IF( NLAYERS .LT. 1 .OR. NLAYERS .GT. MLAYERS )THEN
C       "Number of soil layers out of range 1...MLAYERS"
        SMSPSOFT_UPD = 2
        RETURN
      END IF
C
C *** Compute layer thicknesses
      T(0) = DEPTH(0) * XIN2CM
      T(1) = DEPTH(1) * XIN2CM
      DO I = 2, NLAYERS
        T(I) = (DEPTH(I) - DEPTH(I-1)) * XIN2CM
        IF( T(I) .LE. 0.0 )THEN
C         "Negative or zero soil layer"
          SMSPSOFT_UPD = 3
          RETURN
        END IF
      END DO
C
C     Compute deltat
      DELTAT = MIN( TIME, DTNOM )
      NITER = (TIME+DELTAT/2.)/DELTAT
C
C     Amount of evaporation
      EVAPCM = EVAPRATE * XIN2CM / NITER
C
C     Flow in to surface layer
      RAINCM = RAIN * XIN2CM / NITER
C
      RUNOFFCM = 0.0
      DO ITER = 1, NITER
C
C *** Compute Relative moisture {W}, Permeability {K}, Bubbling
    pressure {PSI}
C       & water volume (as a column depth) {V} for each layer
```

```
         IF( DIAG )WRITE(*,602)
   602   FORMAT(' Lyr  Depth  Thick   Moist     W',
     &           14X,'K',7X,'Psi',9X,'V')
         DO I=0, NLAYERS
           W(I) = ( 0.01 * MOIST(I) - THETAR(ISOIL) ) /
     &              ( THETAS(ISOIL) - THETAR(ISOIL) )
C  Force normalized moisture between field-min (0) & field max (1)
           W(I) = MAX( MIN( W(I), 1.0 ), 0.0 )
           K(I) = KS(ISOIL) * W(I) ** ( 2.0 * GAMMA(ISOIL) + 3.0 )
C
           IF( W(I) .GE. WPSIMAX(ISOIL) ) THEN
C         Normal case ( W > minimum i.e. value at maximum-psi )
             PSI(I) = PSIS(ISOIL) * W(I) ** ( -GAMMA(ISOIL) )
           ELSE
C       Psi goes asymtotic; use straight line at slope of curve at
C  W = WPSIMAX ( MPSIMAX & BPSIMAX computed in routine:
    SMSPSOFT_INIT )
             PSI(I) = MPSIMAX(ISOIL) * W(I) + BPSIMAX(ISOIL)
           END IF
           V(I) = XMC2V( 0.01 * MOIST(I), T(I) )
           IF( DIAG ) WRITE(*,603)
     &      I,DEPTH(I),T(I),MOIST(I),W(I),K(I),PSI(I),V(I)
  603      FORMAT(1X,I2,2F8.1,F8.2,F6.3,1PG15.8,0P,F10.1,F10.5)
         END DO
C
C ***    Compute flow out of each layer
         IF(DIAG)WRITE(*,604)
  604    FORMAT(' Flow rate & volume:'/
     &          ' Lyr',14X,'DeltaV',19X,'Q',16X,'Kbar')
C        Layers 0...n-1
         DO I = 0, NLAYERS-1
          KBAR(I) = ( T(I)*K(I)+T(i+1)*K(I+1) ) / ( T(I) + T(I+1) )
C       Flow rate; Note: Negative = flow out, positive = flow in
           Q(I) = 2.0 * KBAR(I) * ( ( PSI(I) - PSI(I+1) ) /
     &             ( T(I) + T(I+1) ) + 1.0 )
C          Force Q into range +/- KS
           Q(I) = MAX( MIN( Q(I), KS(ISOIL) ), -KS(ISOIL) )
C       Flow amount; Note: Negative = flow out, positive = flow in
           DELTAV(I) = Q(I) * DELTAT * T(I) / T(I+1)
           IF(DIAG)WRITE(*,605)I,DELTAV(I),Q(I),KBAR(I)
  605      FORMAT(1X,I2,1X,1P,3G20.10)
         END DO
C        Layer n
         Q(NLAYERS) = SIN( SLOPE ) * K(NLAYERS)
         DELTAV(NLAYERS) = Q(NLAYERS) * DELTAT
         IF(DIAG)WRITE(*,605)NLAYERS,DELTAV(NLAYERS),Q(NLAYERS)
C
C ***    Maximum flow allowed IN to Layer #0
         S = SQRT( 2.0 * KS(ISOIL) * PSI(0) *
     &       THETAS(ISOIL) * (1.0 - W(0) ) )
         DELTAVW = S * SQRT( DELTAT ) + DELTAV(0)
       IF( DELTAVW .LT. 0) DELTAVW = S * SQRT( DELTAT ) - DELTAV(0)
         IF(DIAG)WRITE(*,606)DELTAVW,S
  606    FORMAT(' Maximum flow into surface layer DELTAVW=',F10.4/
     &          ' ( Sorptivity S =',F10.4,' )')
C
C ***    Update logic
C        Layer #0 (Surface layer)
C  Surface layer cannot accept more than DELTAVW water (minus the
    outflow)
         ACCEPT = DELTAVW - DELTAV(0)
         IF( RAINCM .GT. ACCEPT + EVAPCM )THEN
           VIN = ACCEPT
C          Apply any excess to runoff
           RUNOFFCM = RUNOFFCM + RAINCM - ACCEPT - EVAPCM
         ELSE
           VIN = RAINCM - EVAPCM
```

```
        END IF
C
C       Update amount; current + VIN + out to next layer (NEG=OUT)
        V(0) = V(0) + VIN + DELTAV(0)
C
C       Don't fall below field-min
        V(0) = MAX( V(0), VMIN )

C
        VMAX = XMC2V( THETAS(ISOIL), T(0))
        IF( V(0) .GT. VMAX )THEN
C  If updated amount exceeds field maximum, assume excess is
     runoff
          RUNOFFCM  = RUNOFFCM + V(0) - VMAX
          V(0) = VMAX
        END IF
C       Layers 1...n
        DO I=1, NLAYERS
C  Update amount; current + input from previous layer ( NEG of the
C  out flow from the previous layer) - out to next layer ( NEG of
C         the out flow to the next layer)
          V(I) = V(I) - DELTAV(I-1) + DELTAV(I) + KBAR(I) * DELTAT
          VMIN = XMC2V( THETAR(ISOIL), T(I) )
          VMAX = XMC2V( THETAS(ISOIL), T(I) )
C         Don't exceed field maximum or fall below field minimum
          V(I) = MIN( VMAX, MAX( VMIN, V(I) ) )
        END DO
C ***   Convert water volumes to moisture contents (in percent)
     for return
        DO I=0, NLAYERS
          MOIST(I) = XV2MC( V(I), T(I) ) * 100.
        END DO
      END DO
      RUNOFF = RUNOFFCM / XIN2CM
      IF( DIAG )WRITE(*,613)RUNOFF,(I,MOIST(I),I=0,NLAYERS)
  613 FORMAT(' Routine SMSPSOFT_UPD outputs:'/
     &       3X,'Runoff',T30,F8.0,' (in)'/
     &       3X,'Lyr  Moisture(%)'/100(1X,I4,F10.2/))
C
      RETURN
      END
C SMSPSOFT_INIT Initialize SMSP SOFT
C***********************************
C                    *
C S M S P S O F T _ I N I T *
C                    *
C**************************
      SUBROUTINE SMSPSOFT_INIT()
C
C 14 Sep 98    Initial edit RBA-GL
C
C This routine initializes the SMSP SOFT routine by pre-computing
C the static soil parameters used to extend the Psi vs. W
     relation.
C I.e. it computes the slope and intercept for the extension line.
C
C Inputs:
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C     GAMMA(MSOIL)  Empiracle coefficient used to compute relative
C            permeability and bubbling pressure for each soil type
C     PSIMAX         Maximim PSI for Psi vs. W relation
C     PSIS(MSOIL)   Bubbling pressure head at saturation for each
C              soil type [cm]
C Outputs:
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C  BPSIMAX(MSOIL)   Y-intercept for Psi vs. W extension line, i.e.
C              Psi at W = 0. for each soil type
```

```
C  MPSIMAX(MSOIL)  Slope of Psi vs. W relation at PSIMAX for each
    soil type
C    SOFTINIT      Flag to indicate SOFTINIT has been called
C  WPSIMAX(MSOIL)  Value of W ( relative moisture content) at
    PSIMAX from
C             W vs. Psi relation for each soil type
C
C Internal:
C    A             Temporary PSIS
C    B             Temporary -GAMMA(ISOIL)
C    ISOIL         Soil type loop index
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      INTEGER ISOIL
      REAL A, B
C
      DO ISOIL = 1, MSOIL
        A = PSIS(ISOIL)
        B = -GAMMA(ISOIL)
        WPSIMAX(ISOIL) = EXP( ALOG( PSIMAX / A ) / B )
        MPSIMAX(ISOIL) = A * B * WPSIMAX(ISOIL) ** ( B - 1.0 )
        BPSIMAX(ISOIL) = PSIMAX - MPSIMAX(ISOIL) * WPSIMAX(ISOIL)
      END DO
      SOFTINIT = .TRUE.
      RETURN
      END
C SMSPSOFT_CI Soil strength in Cone Index as a function of
    Moisture content
C*******************************************************************
C             *
C S M S P S O F T _ C I *
C             *
C************************
      REAL FUNCTION SMSPSOFT_CI( ISOIL, MOIST )
C
C  4 Sep 98    Initial edit RBA-GL
C
C  This routine computes the soil strength in Cone Index (CI) as a
C  function of soil moisture content in percent by weight.
C  Coefficients used are from WES TR GL-97-15 "Soil Moisture
C  Strength Prediction Model Version II
C (SMSP II)" pp:33.
C
C Inputs:
C     ISOIL    {i}  Soil type code as follows:
C                   1 =  SW    6 =  CL    11 =  OL
C                   2 =  SP    7 =  ML    12 =  OH
C                   3 =  SM    8 = CLML   13 =  GM
C                   4 =  SC    9 =  CH    14 =  GC
C                   5 = SMSC  10 =  MH
C     MOIST    {r}  Soil moisture content in percent by weight [%]
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C THETAR(MSOIL) Minimum moisture content by weight (field minimum)
C THETAS(MSOIL) Maximum moisture content by weight (field maximum)
C
C Output:
C SMSPSOFT_CI {r} Soil strength in Cone Index corresponding to the
C               given moisture content, or zero if ISOIL is out of
C               range.
C Internal:
C     MAXCI          Maximum soil strength allowed
C     MCADJ        Moisture content adjusted to the range of field
C               minimum and field maximum [%]
C
C Note: Given moisture content is adjusted to be within the
C  appropriate range between field minimum and field maximum.
```

```
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      INTEGER MCOEFS
      PARAMETER ( MCOEFS = 12 )
      REAL COEFS(2,MCOEFS)
C     Arguments:
      INTEGER ISOIL
      REAL MOIST
C     Internal:
      REAL MAXCI, MCADJ
C                        SW                 SP                SM
      DATA COEFS/  3.987,  0.8150,  3.987,  0.8150,  8.749, -
1.1949,
C                        SC                SMSC               CL
     &             9.056, -1.3566,  9.056, -1.3566, 10.998, -
1.8480,
C                        ML                CLML               CH
     &            10.225, -1.5650,  9.454, -1.3850, 13.816, -
5.5830,
C                        MH                 OL                OH
     &            12.321, -2.0440, 10.977, -1.7540, 13.046, -
2.1720/
C
      IF( ISOIL .LT. 1 .OR. ISOIL .GT. 14 ) THEN
        SMSPSOFT_CI = 0.0
      ELSE IF( ISOIL .GT. MCOEFS )THEN
        SMSPSOFT_CI = 300.
      ELSE
C  Force moisture content in range from field minimum to field
maximum
        MCADJ = MIN( THETAS(ISOIL), MAX( THETAR(ISOIL),
     &                 MOIST / 100. ) ) * 100.
        SMSPSOFT_CI = EXP(
COEFS(1,ISOIL)+COEFS(2,ISOIL)*ALOG(MCADJ) )
C       Don't let soil strength exceed allowable maximum
        IF( ISOIL .LE. 2 )THEN
C      Maximum CI for Coarse-grained soils
          MAXCI = 300.0
        ELSE
C      Maximum CI for Finee-grained soils
          MAXCI = 750.0
        END IF
        SMSPSOFT_CI = MIN( SMSPSOFT_CI, MAXCI )
      END IF
      RETURN
      END
C SMSPSOFT_RCI Soil strength in RCI as a function of Moisture
content
C*****************************************************************
C            *
C S M S P S O F T _ R C I *
C            *
C**************************
      REAL FUNCTION SMSPSOFT_RCI( ISOIL, MOIST )
C
C  4 Sep 98    Initial edit RBA-GL
C
C  This routine computes the soil strength in Rating Cone Index
C  (RCI)
C (Cone Index (CI) for soil types SW & SP ) as a function of soil
moisture
C content in percent by weight.  Coefficients used are from WES TR
GL-97-15
C "Soil Moisture Strength Prediction Model Version II (SMSP II)"
pp:34.
C
```

```
C Inputs:
C     ISOIL     {i}  Soil type code as follows:
C                    1 =  SW     6 =  CL    11 =  OL
C                    2 =  SP     7 =  ML    12 =  OH
C                    3 =  SM     8 = CLML   13 =  GM
C                    4 =  SC     9 =  CH    14 =  GC
C                    5 = SMSC   10 =  MH
C     MOIST     {r}  Soil moisture content in percent by weight [%]
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C     THETAR(MSOIL) Minimum moisture content by weight (field
minimum)
C     THETAS(MSOIL) Maximum moisture content by weight (field
maximum)
C
C Output:
C     SMSPSOFT_RCI {r}   Soil strength in Rationg Cone Index
corresponding to
C               the given moisture content, or zero if ISOIL is out
C               of range.
C Internal:
C     THETA          Moisture content adjusted to the range of
field
C               minimum and field maximum
C
C Note: Given moisture content is adjusted to be within the
appropriate
C    range between field minimum and field maximum.
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      INTEGER MCOEFS
      PARAMETER ( MCOEFS = 12 )
      REAL COEFS(2,MCOEFS)
C     Arguments:
      INTEGER ISOIL
      REAL MOIST
C     Internal:
      REAL MCADJ
C                        SW                SP                SM
      DATA COEFS/  3.987,  0.8150,  3.987,  0.8150, 12.542, -
2.9550,
C                        SC                SMSC              CL
     &           12.542, -2.9550, 12.542, -2.9550, 15.506, -
3.5300,
C                        ML                CLML              CH
     &           11.936, -2.4070, 14.236, -3.1370, 13.686, -
2.7050,
C                        MH                OL                OH
     &           23.641, -5.1910, 17.399, -3.5840, 12.189, -
1.9420/
C
      IF( ISOIL .LT. 1 .OR. ISOIL .GT. 14 ) THEN
        SMSPSOFT_RCI = 0.0
      ELSE IF( ISOIL .GT. MCOEFS )THEN
        SMSPSOFT_RCI = 300.
      ELSE
C       Force moisture content in range from field minimum to
field maximum
        MCADJ = MIN( THETAS(ISOIL), MAX( THETAR(ISOIL),
     &               MOIST / 100. ) ) * 100.
        SMSPSOFT_RCI = EXP(
COEFS(1,ISOIL)+COEFS(2,ISOIL)*ALOG(MCADJ) )
C    Don't let soil strength exceed maximum allowed
        SMSPSOFT_RCI = MIN( SMSPSOFT_RCI, 750.0 )
      END IF
      RETURN
      END
```

```
C SMSPSOFT_MC_SET Set moisture content for MSPSOFT
C*************************************************
C                         *
C S M S P S O F T _ M C _ S E T *
C                         *
C*********************************
      REAL FUNCTION SMSPSOFT_MC_SET( ISOIL, RATIO )
C
C  8 Sep 98    Initial edit RBA-GL
C
C     This routine sets soil moisture content to a reasonable
value based
C on wetness index:
C
C Inputs:
C     ISOIL    {i}  Soil type code as follows:
C                   1 =  SW    6 =  CL    11 =  OL
C                   2 =  SP    7 =  ML    12 =  OH
C                   3 =  SM    8 = CLML   13 =  GM
C                   4 =  SC    9 =  CH    14 =  GC
C                   5 = SMSC  10 =  MH
C     RATIO    {i}  Proportion between field-minimum and field-
maximum
C              to set moisture content
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C     THETAR(MSOIL) Minimum moisture content by weight (field
minimum)
C     THETAS(MSOIL) Maximum moisture content by weight (field
maximum)
C Output:
C     SMSPSOFT_MC_SET {r} Moisture content in percent by weight,
or zero if
C              any input arguments are out of range [%]
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      INTEGER ISOIL
      REAL RATIO
      IF( ISOIL .LT. 1 .OR. ISOIL .GT. MSOIL .OR.
     &    RATIO .LT. 0 .OR. RATIO .GT. 1.0 )THEN
        SMSPSOFT_MC_SET = 0.0
      ELSE
        SMSPSOFT_MC_SET = THETAR(ISOIL) + RATIO *
     &                  ( THETAS(ISOIL)-THETAR(ISOIL) ) * 100.0
      END IF
      RETURN
      END
C SMSPSOFT_STATIC Static soil parameters for SMSPSOFT model
C**********************************************************
C                         *
C S M S P S O F T _ S T A T I C *
C                         *
C*********************************
      BLOCK DATA SMSPSOFT_STATIC
C
C  3 Sep 98    Initial edit RBA-GL
C
C     This is the static soil parameter data for the SMSPSOFT
model.
C
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C     DENSITY(MSOIL)     Density of each soil type [lb/ft^3]
C     GAMMA(MSOIL)  Empiracle coefficient used to compute relative
C              permeability and bubbling pressure for each soil
type
C     KS(MSOIL)          Saturated permeability (flow rate) for
each soil
```

```
C               type [cm/sec]
C      PSIMAX         Maximum Psi allowed for W vs. Psi relation
C      PSIS(MSOIL)    Bubbling pressure head at saturation for each
C               soil type [cm]
C      THETAR(MSOIL) Minimum moisture content by weight (field
minimum)
C      THETAS(MSOIL) Maximum moisture content by weight (field
maximum)
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
C
      DATA SOFTINIT /.FALSE./
      DATA PSIMAX / 100000. /
C
C                        SW        SP        SM        SC      SMSC
C                        CL        ML      CLML        CH        MH
C                        OL        OH        GM        GC
      DATA DENSITY/   93.60,    93.60,    93.70,    97.40,   100.50,
     &                86.80,    73.70,    93.70,    85.50,    66.20,
     &                77.40,    52.50,   120.00,   120.00 /
C     The following is from Table 25 pg 28 of GL-97-15
      DATA GAMMA  /    1.852,    1.852,    2.375,    2.667,    2.597,
     &                 4.505,    4.202,    4.292,    5.208,    4.878,
     &                 3.876,    4.237,    3.247,    4.065 /
      DATA KS     / 0.00762, 0.00762, 0.00861, 0.00384, 0.00484,
     &              .000603, .000792, .000848, .000376, 0.00042,
     &              0.00122, .000883, 0.00298, 0.00174 /
      DATA PSIS   /     16.6,     16.6,     14.1,     18.4,     17.2,
     &                  33.5,     33.9,     32.9,     32.9,     39.0,
     &                  28.6,     29.3,     12.7,     23.2 /
C     Field minimum moisture content
      DATA THETAR /   0.016,    0.016,    0.026,    0.056,    0.048,
     &                0.036,    0.026,    0.026,    0.071,    0.038,
     &                0.030,    0.041,    0.041,    0.034 /
C     Field maximum moisture content
      DATA THETAS /   0.347,    0.438,    0.408,    0.419,    0.418,
     &                0.469,    0.537,    0.468,    0.569,    0.547,
     &                0.627,    0.892,    0.438,    0.452 /
C
      END
C EVAPORATION for checkout 21 Sep 98
C*************************
C          *
C E V A P O R A T I O N *
C          *
C*************************
      REAL FUNCTION EVAPORATION ( DELTAT, ISOIL, MOIST, THICK )
C
C *** THIS IS FOR CHECKOUT ONLY ***
C
C     This function provides evaporation amount as a column of
water (in)
C as a functionon of moisture in the surface layer for the given
time period.
C For checkout, evaporation is a constant of 140 inch/inch/year
times the
C amout of water in the surface layer in inch/inch.
C
C
C Inputs:
C     DELTAT    {r}  Time period [sec]
C     ISOIL     {i}  Soil type code as follows:
C                    1 =  SW     6 =  CL    11 =  OL
C                    2 =  SP     7 =  ML    12 =  OH
C                    3 =  SM     8 = CLML   13 =  GM
C                    4 =  SC     9 =  CH    14 =  GC
```

```
C                    5 = SMSC  10 =  MH
C     MOIST     {r}  Soil surface moisture content (percent by
weight) [%]
C     THICK     {r}  Surface layer thickness [in]
C   Common /SMSPSOFTSTATIC/ Static soil parameters
C     DENSITY(MSOIL)     Density of each soil type [lb/ft^3]
C
C Output:
C     EVAPORATION {r}    Surface evaporation as a column of water
[in]
C Internal:
C     VOL       Moisture content as a column of water [in]
C     WATER            Density of water, [lbs/ft^3]
C
      IMPLICIT NONE
      INCLUDE 'smspsoft.inc'
      LOGICAL DIAG
      COMMON /SMSPSOFTDIAG/DIAG
C
C     Arguments:
      INTEGER ISOIL
      REAL DELTAT, EVAPRATE, MOIST, THICK
C     Internal:
      REAL VOL
C     140 in/in/year converted to in/in/sec.
*     PARAMETER ( EVAPRATE = 140./365./24./60./60. )
      PARAMETER ( EVAPRATE = .002/60./60. )
C
C     Volume of water in surface layer
      VOL = 0.01 * MOIST * THICK * DENSITY(ISOIL) / WATER
      EVAPORATION = EVAPRATE * VOL * DELTAT
      IF( DIAG )WRITE(*,601)DELTAT, MOIST, THICK, THICK*2.54, VOL,
     &                        VOL*2.54, EVAPRATE, EVAPORATION,
     &                        EVAPORATION*2.54
  601 FORMAT(' Routine: EVAPORATION:'/
     &        3X,'Time',T30,'DELTAT',T45,F8.1,' (sec)'/
     &        3X,'Moisture content',T30,'MOIST',T45,F8.3,' (%)'/
     &        3X,'Layer thickness',T30,'THICK',T45,F8.5,' (in)',
     &           F8.5,' (cm)'/
     &        3X,'Moisture volume',T30,'VOL',T45,F8.5,' (in)'
     &           F8.5,' (cm)'/
     &        3X,'Evaporation rate',T30,'EVAPRATE',T40,G13.5,
     &           ' (in/in/sec)'/
     &        3X,'Evaporation amount',T30,'EVAPORATION',
     &           T45,F8.5,' (in)',F8.5,' (cm)')
      RETURN
      END
```

Table A1
Quantification of Wheels Study Definitions of Tactical Mobility

Mobility Level	Operating Distance, Percent		Off-Road[2] Percent of Terrain Challenged	On-Road Percent of Trails Challenged
	Off-Road	On-Road[1]		
High-High Mobility = All off-road operations	100	0	100	--
Tactical High Mobility = The highest level of mobility designating the requirements for extensive cross-country maneuverability characteristics of combat operations in the ground-gaining and fire-support environment.	50	50	90	100
Tactical Standard Mobility = The second highest level of mobility designating the requirement for occasional cross-country movement, characteristic of combat support operations.	15	85	80	100
Tactical Support Mobility = A level of mobility designating the requirement for infrequent off-road operations over selected terrain with the preponderance of movement on primary and secondary roads, characteristic of combat service support operations.	5	95	50	80
On-Road Mobility[3]= All on superhighways, primary and secondary roads, and the best tertiary roads and trails.	0	100	--	50

[1] From Ahlvin and Haley (1992).
[2] In terms of percentage of best off-road terrain to be challenged (off-road speed profile).
[3] Not a WHEELS Study definition, but added during HIMO Study to yield a continuum for all off-road to all on-road travel.

Table A2
Network Composition and Severity at Tactical Mobility Levels for Study Area Indicated

Mobility Levels	Composition of Network in Percent				Severity of Operation in Terms of Percent of Terrain and Roads Challenged[1]			
	Primary Roads (P_P)	Secondary Roads (P_S)	Trails (P_T)	Off-Road (P)	Primary Roads (V_{PP})	Secondary Roads (V_{SP})	Trails (V_{PP})	Off-Road (V_c)
Central Europe								
High-High	0	0	0	100	--	--	--	V_{100}
Tactical High	10	30	10	50	V_{100}	V_{100}	V_{100}	V_{90}
Tactical Standard	20	50	15	15	V_{100}	V_{100}	V_{100}	V_{80}
Tactical Support	30	55	10	5	V_{100}	V_{100}	V_{80}	V_{50}
On-Road	35	60	5	0	V_{100}	V_{100}	V_{50}	--
Far East								
High-High	0	0	0	100	--	--	--	V_{100}
Tactical High	10	30	10	50	V_{100}	V_{100}	V_{100}	V_{90}
Tactical Standard	20	50	15	15	V_{100}	V_{100}	V_{100}	V_{80}
Tactical Support	30	55	10	5	V_{100}	V_{100}	V_{80}	V_{50}
On-Road	35	60	5	0	V_{100}	V_{100}	V_{50}	--
Middle East								
High-High	0	0	0	100	--	--	--	V_{100}
Tactical High	5	20	25	50	V_{100}	V_{100}	V_{100}	V_{90}
Tactical Standard	15	35	35	15	V_{100}	V_{100}	V_{100}	V_{80}
Tactical Support	20	40	35	5	V_{100}	V_{100}	V_{80}	V_{50}
On-Road	30	45	30	0	V_{100}	V_{100}	V_{50}	--

[1] Percent of terrain challenged refers to the average speed of the vehicle over a given percent of the best terrain. For instance, V_{90} means the speed of the vehicle negotiating 90 percent of the terrain with the higher speeds and avoiding 10 percent of the terrain with the lowest speeds.

Appendix B
Real-Time Mobility API for SAF

```
C GRIZAPI API for NRMM plowing model predictions of Grizzly 22 Sep 98
C***************************************************
C
C   GGGG  RRRR    III   ZZZZZ     A     PPPP    III
C  G      R   R    I       Z     A A    P   P    I
C  G  gg  RRRR     I      Z     A   A   PPPP     I
C  G   g  R  R     I     Z     AAAAA    P        I
C   GGG   R   R   III   ZZZZZ  A    A   P       III
C
C***************************************************
      SUBROUTINE grizzly_plowing_speed( null, Yin, plowspeed )
C
C  6 Oct 98   Initial edit
C
C  This routine is an special API interfacing for NRMM predictions
C for the Grizzly mine plow.
C
C Inputs:
C     null    unused argument
C     Yin(0:7) Terrain data input as follows:
C             Yin(0)      Plow depth [in]
C             Yin(1)      ITD soil type code:
C                         0 = Unknown     7 = SM   ..............14 = OH
C                         1 = GW  8 = SC          15 = Pt
C                         2 = GP  9 = ML          16 = Not Used
C                         3 = GM 10 = CL          17 = Not Used
C                         4 = GC 11 = OL          18 = Not Used
C                         5 = SW 12 = CH
C                         6 = SP 13 = MH
C             Note: and value out of range [1..14] will be assigned 8
(SC)
C             Yin(2)      Vegetation cover code:
C                         0 = Bare
C                         1 = Grass
C                         2 = Forest
C             Yin(3) CCTT Slope class code:
C             Code        Range          Value used
C               1         <= -60         -60
C               2          -40 to <-60   -50
C               3          -20 to <-40   -30
C               4           -5 to <-20   -13
C               5           >0 to <-5    -3
C               6       =0                0
C               7       >0 to <5          3
```

```
C              8           5 to <20    13
C              9          20 to <40    30
C             10          40 to <60    50
C             11          >= 60        60
C  Note: Any slope class codes outside the range [1..11]
C        will be assiged code = 6 ( slope = 0 )
C  Yin(4)    Moisture content of soil surface layer (from SMSP/SOFT)
C                    [% by weight]
C  Yin(5)    Moisture content of 0"-12" soil layer (from SMSP/SOFT)
C                    [% by weight]
C  Yin(6)    Soil strength of soil surface (from SMSP/SOFT) [CI|RCI]
C  Yin(7)    Soil strength of 0"-12" soil layer (from SMSP/SOFT)
C                    [CI|RCI]
C
C Output:
C  plowspeed  Vehicle speed [meters/sec]; zero returned for "NO-GO" or
errors
C
      IMPLICIT NONE
      INCLUDE 'grizapic.inc'
C
      INTEGER NULL
      REAL plowspeed, Yin(0:7)
C
      LOGICAL FIRST, INIT
      INTEGER GRIZ_PLOW_INIT
      REAL PFORCE
      REAL GRIZ_PLOW_FORCE, GRIZ_PLOW_SPEED
      CHARACTER *60 FPATH
      SAVE FIRST, INIT
      DATA FPATH /'Grizzly.dat'/
      DATA FIRST /.TRUE./
C
C *** First time open data file & read Grizzly plow performance data
      IF( FIRST )THEN
    INIT = GRIZ_PLOW_INIT(FPATH) .EQ. 0
        FIRST = .FALSE.
      END IF
      IF(DIAG)write(*,*)'Yin=',Yin
C
C     Check for proper initialization
      IF( INIT .AND.
C       And check for non forested areas
     &    Yin(Veg) .NE. FOREST )THEN
    Pforce = GRIZ_PLOW_FORCE( Yin(Depth), Yin(SoilStren),
     &                          Yin(ITDSoiltype) )
        IF( Pforce .LT. GCW )THEN
      PlowSpeed = GRIZ_PLOW_SPEED( Pforce, Yin(SoilStren),
     &                              Yin(ITDSoiltype), Yin(CCTT) )
        ELSE
      PlowSpeed = 0.0
        END IF
      ELSE
    PlowSpeed = 0.0
      END IF
C
      PlowSpeed = PlowSpeed * XMPH2MPS
C
      RETURN
      END
C GRIZ_PLOW_SPEED Compute plowing speed 18 Nov 98
C***************************************
```

```
C                                *
C G R I Z _ P L O W _ S P E E D *
c                                *
C********************************
      REAL FUNCTION GRIZ_PLOW_SPEED( Pforce, SoilStr, ITD, CCTTSLOPE )
C
C  6 Oct 98   Initial edit
C
C Inputs:
C      ITD      ITD soil type code:
C                          0 = Unknown     7 = SM   ..............14 = OH
C                          1 = GW  8 = SC          15 = Pt
C                          2 = GP  9 = ML          16 = Not Used
C                          3 = GM10 = CL           17 = Not Used
C                          4 = GC11 = OL           18 = Not Used
C                          5 = SW12 = CH
C                          6 = SP         13 = MH
C      PFORCE  Plow force [lb]
C      SOILSTR Soil strength [CI or RCI]
C   Common /GRIZAPI/
C      B(3,MSOILT,NSTREN,0:1)     Tractive force vs. Speed hyperbola
coefficients
C                          for each soil type, strength & surface
condition of the
C                          form:
C                                    B(1,...)
C                     TFcoef = ---------------- + B(2,...)
C                                 Speed + B(3,...)
C
C      GCW                Gross combined weight [lb]
C      HPCOEF      Power-train power reduction coefficient penalty for
C                          using plow (1.0=no reduction, 0.0 = 100%
reduction)
C      NSTREN      Number of soil strengths
C      RESCOEF(MSOILS,NSTREN,0:1) Resistance coefficient
C      STCOEF      Surface traction reduction coefficient penalty for
C                          operating on plowed surface (1.0=no
reduction, 0.0=full
C                          reduction)
C      STREN(NSTREN)       Soil strength values [CI/RCI]
C      TFOWMN(MSOILT,NSTREN,0:1) Minimum tractive force limit
coefficient for
C                          each soil type, strength & surface condition
C      TFOWMX(MSOILT,NSTREN,0:1) Maximum tractive force limit
coefficient for
C                          each soil type, strength & surface condition
C Internal:
C
C      ISOILT  Internal soil type code as follows:
C                       1 = USCS types SC, GC
C                       2 = USCS types CH, MH, OH
C                       3 = USCS types ML, ML-CL, CL, OL
C                       4 = USCS types SM, SM-SC, GM, GM-GC
C                       5 = USCS types SP, SW, GP, GW
C                       6 = USCS type Pt
C
      IMPLICIT NONE
      INCLUDE 'grizapic.inc'
C
      REAL CCTTSLOPE, ITD, PFORCE, SOILSTR
C
      REAL XDEG2RAD
```

```
      PARAMETER ( XDEG2RAD = 3.1415926/180. )
C
      LOGICAL IFIND
      INTEGER I, I1, I2, ISLPRY, ISOILT, ISTREN, KCCTT, KITD
      INTEGER KXLITD(15)
      REAL CIRCI, FACT, SLOPE, TANSLOPE, TFOW
      REAL CCTTSLOPES(11),ROW(2),SP(2)
      PARAMETER ( ISLPRY = 0 )
C
C                 GW GP GM GC SW SP SM SC ML CL
      DATA KXLITD/ 5, 5, 4, 1, 5, 5, 4, 1, 3, 3,
C                 OL CH MH OH Pt
     &             3, 2, 2, 2, 6/
      DATA CCTTSLOPES/-60.,-50.,-30.,-13.,-3.,0.,3.,13.,30.,50.,60./
C
      IF(DIAG)THEN
        WRITE(*,*)'Routine: GRIZ_PLOW_SPEED Inputs:'
        WRITE(*,*)'Pforce=',PFORCE,' SoilStr=',SOILSTR,' ITD=',ITD
        WRITE(*,*)'CCTTSLOPE=',CCTTSLOPE
      END IF
C
      DIAG_ROW   = 0.0
      DIAG_SLOPE = 0.0
C
C     Check to see if data has been read O-K
      IF( NSTREN .LE. 0 )THEN
        GRIZ_PLOW_SPEED = 0.0
        RETURN
      END IF
C
C     Translate ITD soil code to internal code:
      KITD = ITD
      IF( KITD .GT. 0 .AND. KITD .LE. 15 )THEN
         ISOILT = KXLITD( KITD )
      ELSE
        GRIZ_PLOW_SPEED = 0.0
        RETURN
      END IF
C
C     Translate CCTT slope code to actual slope
      KCCTT = CCTTSLOPE
      IF( KCCTT .GT. 0 .AND. KCCTT .LE. 11 )THEN
        SLOPE = CCTTSLOPES( KCCTT ) * XDEG2RAD
        TANSLOPE = TAN( SLOPE )
        DIAG_SLOPE = TANSLOPE
      ELSE
        GRIZ_PLOW_SPEED = 0.0
        RETURN
      END IF
      IF(DIAG)WRITE(*,*)'Output: ISOILT=',ISOILT,
     &                  ' SLOPE=',SLOPE/XDEG2RAD
C
C     Force soil strength to within range of given data
      CIRCI = MIN( MAX( SOILSTR, MIN( STRENS(1), STRENS(NSTREN) ) ),
     &          MAX( STRENS(1),STRENS(NSTREN) ) )
C     Find indices (I1 & I2) of table values surrounding soil strength
      IF( IFIND( I1, FACT, CIRCI, STRENS, NSTREN ) )THEN
        I2 = I1 + 1
C       Get speeds for STRENS(i) & STRENS(i+1)
        ISTREN=I1
        DO I=1,2
          ROW(I) = RESCOEF(ISTREN,ISOILT,ISLPRY)
```

```
C         Sum all resistances (Plow + motion resistance + slope)
          TFOW = PFORCE / GCW + ROW(I) + TANSLOPE
          IF( TFOW .GT. TFOWMX(ISTREN,ISOILT,ISLPRY)*STCOEF ) THEN
            SP(I) = 0.0
          ELSE
C           Force to be in range of function
            TFOW = MAX( TFOW, TFOWMN(ISTREN,ISOILT,ISLPRY) )
            IF( STCOEF .GT. 0.0 .AND.
     &          HPCOEF .GT. 0.0 ) THEN
              SP(I) = HPCOEF * B(1,ISTREN,ISOILT,ISLPRY) /
     &            ( TFOW / STCOEF - B(2,ISTREN,ISOILT,ISLPRY) *
     &              HPCOEF ) - B(3,ISTREN,ISOILT,ISLPRY)
C             Don't let speed be less than zero
            ELSE
              SP(I)=0.0
            END IF
          END IF
          IF( ISTREN .EQ. NSTREN )EXIT
          ISTREN = I2
        END DO
C
C       Interpolate speed for given soil strength
        GRIZ_PLOW_SPEED = ( SP(2) - SP(1) ) * FACT + SP(1)
C       Don't let speed be less than zero
        GRIZ_PLOW_SPEED = MAX( GRIZ_PLOW_SPEED, 0.0 )
C       Interpolate resistance for diagnostics
        DIAG_ROW = ( ROW(2) - ROW(1) ) * FACT + ROW(1)
      ELSE
        GRIZ_PLOW_SPEED = 0.0
      END IF
C
      RETURN
      END
C GRIZ_PLOW_FORCE Compute plowing resistance force 18 Nov 98
C***********************************************
C                              *
C G R I Z _ P L O W _ F O R C E *
C                              *
C*******************************
      REAL FUNCTION GRIZ_PLOW_FORCE( Pdepth, SoilStr, ITD )
C
C  7 Oct 98   Initial edit
C
C
C Inputs:
C     ITD     ITD soil type code:
C                       0 = Unknown     7 = SM   14 = OH
C                       1 = GW  8 = SC           15 = Pt
C                       2 = GP  9 = ML           16 = Not Used
C                       3 = GM10 = CL            17 = Not Used
C                       4 = GC11 = OL            18 = Not Used
C                       5 = SW12 = CH
C                       6 = SP13 = MH
C     PDEPTH  Plowing depth [in]
C     SOILSTR Soil strength [CI or RCI]
C   Common /GRIZAPI/
C     NPDEPTH             Number of plow data plowing depths given
C     NPSTREN             Number of soil strengths, plow data
C     PDEPTHS(NPDEPTH)Plowing depths [in]
C     PFORCES(NPDEPTH,NPSTREN,MSOILS)  Plowing force [lb] for each
depth,
C     PSTREN(NSTREN)      Soil strength values for plow data [CI/RCI]
```

```
C
C Internal:
C     F(2)     Plow force for soil strengths PSTRENS(K1) & PSTRENS(K1+1)
C     FACTJ    Interpolation factor for depths
C     FACTK    Interpolation factor for soil strengths
C     FP       Interpilated plow force
C     I                  Loop indez for 2 force points F(I)
C     ISOILT   Internal soil type code as follows:
C                      1 = USCS types SC, GC
C                      2 = USCS types CH, MH, OH
C                      3 = USCS types ML, ML-CL, CL, OL
C                      4 = USCS types SM, SM-SC, GM, GM-GC
C                      5 = USCS types SP, SW, GP, GW
C                      6 = USCS type Pt
C     ISTAT    Internal status code:
C                   2 = No depth data given
C                   3 = No soil strength data given
C                   4 = Bad soil code given
C                   5 = Input depth data out of range
C                   6 = Only one depth given in data &
C                          input depth not equal to it
C                      7 = Input soil strength data out of range
C     J1       I-th point for interpolation in PDEPTHS array; PDEPTH is
C                    between PDEPTHS(K1) & PDEPTHS(K1+1)
C     K1       I-th point for interpolation in PSTRENS array; SOILSTR is
C                    between PSTRENS(K1) & PSTRENS(K1+1)
C     KITD     ITD soil code index
C
      IMPLICIT NONE
      INCLUDE 'grizapic.inc'
C
      REAL ITD, PDEPTH, SOILSTR
C
      LOGICAL IFIND
      INTEGER I, J1, K1, ISOILT, ISTAT, KITD
      INTEGER KXLITD(15)
      REAL F(2), FACTJ, FACTK, FP
C
C                GW GP GM GC SW SP SM SC ML CL
      DATA KXLITD/ 5, 5, 4, 1, 5, 5, 4, 1, 3, 3,
C                OL CH MH OH Pt
     &            3, 2, 2, 2, 6/
C
      IF(DIAG)THEN
        WRITE(*,*)'Routine: GRIZ_PLOW_FORCE Inputs:'
        WRITE(*,*)'Pdepth=',PDEPTH,' SoilStr=',SOILSTR,' ITD=',ITD
      END IF
C
      ISTAT = 0
C
      IF( PDEPTH .LE. 0.0 )THEN
C       No plow depth, force is zero
        GRIZ_PLOW_FORCE = 0.0
      ELSE IF( NPDEPTH .LE. 0 ) THEN
C  No depth data given, return high force
        ISTAT = 2
      ELSE IF( NPSTREN .LE. 0 ) THEN
C  No soil strength data given, return high force
        ISTAT = 3
      ELSE
C       Translate ITD soil code to internal code:
        KITD = ITD
```

```
          IF( KITD .GT. 0 .AND. KITD .LE. 15 )THEN
            ISOILT = KXLITD( KITD )
          ELSE
 C     Bad soil code given
            ISTAT = 4
          END IF
 C
          IF( ISTAT .EQ. 0 )THEN
 C     Find indices for soil strength
            IF( IFIND( K1, FACTK, SOILSTR, PSTRENS, NPSTREN ) )THEN
              IF( NPDEPTH .EQ. 1 .AND. PDEPTH .EQ. PDEPTHS(1) ) THEN
                FP = PFORCES( 1,K1,ISOILT )
           IF( K1 .LT. NPSTREN ) FP = FP +
      &           ( PFORCES(1,K1+1,ISOILT) - FP ) * FACTK
                GRIZ_PLOW_FORCE = FP
              ELSE IF( NPDEPTH .GT. 1 )THEN
                IF( IFIND( J1, FACTJ, PDEPTH, PDEPTHS, NPDEPTH ) )THEN
                  DO I=1,2
                    F(I) = PFORCES(J1,K1,ISOILT)
                    IF( K1 .LT. NPSTREN ) F(I) = F(I) +
      &               ( PFORCES(J1,K1+1,ISOILT) - F(I) ) * FACTK
                    J1=J1+1
                    IF( J1 .GT. NPSTREN )EXIT
                  END DO
                  FP = F(1)
                  IF( J1 .LE. NPSTREN ) FP = FP + ( F(2) -FP ) * FACTJ
                  GRIZ_PLOW_FORCE = FP
                ELSE
 C                Input depth data out of range
                  ISTAT = 5
                END IF
              ELSE
 C          Only one depth given in data; input depth not equal to it
                ISTAT = 6
              END IF
            ELSE
 C            Input soil strength data out of range
              ISTAT = 7
            END IF
          END IF
        END IF
 C
 C     Return high plow force if any errors (error status is a multiple
 of GCW)
        IF(ISTAT.NE.0)GRIZ_PLOW_FORCE = GCW * ISTAT
        DIAG_PFORCE = GRIZ_PLOW_FORCE
 C
        IF(DIAG)WRITE(*,*)'Output: GRIZ_PLOW_FORCE=',GRIZ_PLOW_FORCE,
      &                   ' Coef.=',GRIZ_PLOW_FORCE/GCW
 C
        RETURN
        END
 C GRIZ_PLOW_INIT Initialize Grizzly plowing
 C*******************************************
 C                             *
 C G R I Z _ P L O W _ I N I T *
 C                             *
 C*****************************
        INTEGER FUNCTION GRIZ_PLOW_INIT( FPATH )
 C
 C  6 Oct 98   initial edit
 C
```

```
C     Thid routine populates the Grizzly plow model internal tables
from
C an external data file.
C
C Input:
C     FPATH   Path name to Grizzly plow performance information data
C Outputs:
C     GRIZ_PLOW_INIT      Initialization status:
C                            0 = O-K
C                          Pos = I/O error; system specific I/O status
returned
C                           -1 = Premature E.O.F. reading input data
C                           -2 = No logical unit available for file I/O
C                           -3 = NSTREN out of range [2..MSTREN]
C                           -4 = NPDEPTH out of range [0..MPDEPTH]
C                           -5 = NPSTREN) out of range [2..MPSTREN]
C                           -6 = Unexpected soil type code reading
vehicle data
C                           -7 = Soil strength mis-match reading
vehicle data
C                           -8 = Unexpected soil type code reading plow
data
C                           -9 = Soil strength mis-match reading plow
data
C   Common /GRIZAPI/
C     B(3,MSOILT,NSTREN,0:1)    Tractive force vs. Speed hyperbola
coefficients
C                         for each soil type, strength & surface
condition of the
C                         form:
C                                    B(1,...)
C                    TFcoef = ---------------- + B(2,...)
C                                 Speed + B(3,...)
C
C     GCW               Gross combined weight [lb]
C     HPCOEF   Power-train power reduction coefficient penalty for
C                         using plow (1.0=no reduction, 0.0 = 100%
reduction)
C     NSTREN   Number of soil strengths, or zero if there is an error
C     RESCOEF(MSOILS,NSTREN,0:1) Resistance coefficient
C     STCOEF   Surface traction reduction coefficient penalty for
C                         operating on plowed surface (1.0=no
reduction, 0.0=full
C                         reduction)
C     STREN(NSTREN)  Soil strength values [CI/RCI]
C     TFOWMN(MSOILT,NSTREN,0:1) Minimum tractive force limit
coefficient for
C                         each soil type, strength & surface condition
C     TFOWMX(MSOILT,NSTREN,0:1) Maximum tractive force limit
coefficient for
C                         each soil type, strength & surface condition
C
C Internal:
C     Bin(3)   Input tractive force coefficient vs speed hyperbola
coefficients
C     I                   Tractive force coefficient vs speed hyperbola
coefficient
C                         loop index
C     ISLPRY   Surface condition index: 0=normal, 1=slippery
C     ISOILT   Soil type loop index
C     ISTIN    Input soil type code
C     ISTREN   Soil strength loop index
```

```
C
      IMPLICIT NONE
      INCLUDE 'grizapic.inc'
C
      CHARACTER *(*) FPATH
C
      INTEGER I, IOSTAT, IPDEPTH, IPSTREN, ISLPRY, ISOILT,
     &        ISTREN, ISTIN, LDEV, NREC
      INTEGER LDEVUNQ
      REAL CIRCI
C
      NAMELIST /GRIZDATA/GCW, DIAG, HPCOEF, NPDEPTH, NPSTREN, NSTREN,
     &                    PDEPTHS, PSTRENS, STCOEF, STRENS
C
      DIAG=.FALSE.
C
C     Get an unused logical unit number
      LDEV=LDEVUNQ()
      IF(LDEV.LE.0)THEN
C       Logical unit unavailable

        IOSTAT = -2
      ELSE
        OPEN( UNIT=LDEV, FILE=FPATH, STATUS='OLD', IOSTAT=IOSTAT)
        IF(DIAG.AND.IOSTAT.NE.0)WRITE(*,*)
     &   'OPEN: "',CHARNB(FPATH),'" IOSTAT=',IOSTAT
        IF(IOSTAT.EQ.0)READ(UNIT=LDEV,NML=GRIZDATA,IOSTAT=IOSTAT)
        IF(DIAG.AND.IOSTAT.NE.0)WRITE(*,*)
     &   'READ /GRIZDATA/: IOSTAT=',IOSTAT
C
C       Check input data so far
        IF(IOSTAT.EQ.0)THEN
          IF( NSTREN .LT. 2 .OR. NSTREN .GT. MSTREN )THEN
C           No. of vehicle performance soil strengths out of range
[2..MSTREN]
        IOSTAT = -3
          ELSE IF( NPDEPTH .LT. 0 .OR. NPDEPTH .GT. MPDEPTH ) THEN
C       Number of plow depths out of range [0..MPDEPTH]
            IOSTAT = -4
      ELSE IF( NPDEPTH .GT. 0 .AND.
     &           ( NPSTREN .LT. 2 .OR. NPSTREN .GT. MPSTREN ) )THEN
C           Number of plow soil strengths (NPSTREN) out of range
[2..MPSTREN]
            IOSTAT = -5
          END IF
        END IF
C
C       Read vehicle performance information
        IF( IOSTAT .EQ. 0 )THEN
          NREC=0
          DO ISLPRY = 0, 1
            DO ISOILT = 1, MSOILS
              DO ISTREN = 1, NSTREN
                READ(LDEV,*,IOSTAT=IOSTAT)
     &            ISTIN, CIRCI,
     &................................. RESCOEF(ISTREN,ISOILT,ISLPRY),
     &.................................. TFOWMX(ISTREN,ISOILT,ISLPRY),
     &.................................. TFOWMN(ISTREN,ISOILT,ISLPRY),
     &           (B(I,ISTREN,ISOILT,ISLPRY),I=1,3)
                NREC=NREC+1
          IF( IOSTAT.EQ. 0 )THEN
                  IF( ISTIN .NE. ISOILT )THEN
```

```
C                   Unexpected soil type code reading vehicle
performance
                    IOSTAT = -6
                    IF(DIAG)THEN
                      WRITE(*,*)'NREC=',NREC,' ISTIN=',
     &                 ISTIN,' CIRCI=',CIRCI
                      WRITE(*,*)' Unexpected soil type code',
     &                 ' reading vehicle performance data'
                      WRITE(*,*)'Read: ',ISTIN,' expected:',ISOILT
                    END IF
                  ELSE IF( STRENS(ISTREN) .NE. CIRCI )THEN
C    ................    I/P soil strength for current soiltype (ISOILT)
C    ............................    does not match one given in STRENS
     ..............................................    IOSTAT = -7
                    IF(DIAG)THEN
                      WRITE(*,*)'NREC=',NREC,' ISTIN=',
     &                 ISTIN,' CIRCI=',CIRCI
                      WRITE(*,*)' Unexpected soil strength',
     &                 ' reading vehicle performance data'
                      WRITE(*,*)'Read: ',CIRCI,
     &                 ' expected:',STRENS(ISTREN)
                    END IF
                  END IF
                END IF
                IF( IOSTAT.NE.0 )EXIT
              END DO
              IF( IOSTAT.NE.0 )EXIT
            END DO
            IF( IOSTAT.NE.0 )EXIT
          END DO
        END IF
C
C       Read plow performance information
        IF( IOSTAT.EQ.0 .AND. NPDEPTH .GT. 0 )THEN
C     Read plow force data
C         First read
          DO ISOILT = 1, MSOILS
        DO IPSTREN = 1, NPSTREN
              READ(LDEV,*,IOSTAT=IOSTAT)
     &          ISTIN, CIRCI, ( PFORCES(IPDEPTH,IPSTREN,ISOILT),
     &                          IPDEPTH = 1, NPDEPTH )
              IF( IOSTAT .EQ. 0 )THEN
            IF( ISTIN .NE. ISOILT ) THEN
C                 Unexpected soil type code for plow performance data
              IOSTAT = -8
                ELSE IF( PSTRENS(IPSTREN) .NE. CIRCI )THEN
C             I/P soil strength for current plow soiltype (ISOILT)
C             does not match same one given in PSTRENS
              IOSTAT = -9
                END IF
              END IF
              IF( IOSTAT.NE.0 )EXIT
            END DO
            IF( IOSTAT.NE.0 )EXIT
          END DO
        END IF
C
      END IF
      GRIZ_PLOW_INIT = IOSTAT
C     If not O-K, flag problem by setting NSTREN, NPSTREN & NPDEPTH = 0
      IF( IOSTAT .NE. 0 )THEN
   NSTREN = 0
```

```
    NPSTREN = 0
    NPDEPTH = 0
      END IF
C
      IF(DIAG)CALL ECHO_GRIZZLY_DATA( IOSTAT )
C
      RETURN
      END
C ECHO_GRIZZLY_DATA Echo Grizzly input data to system output
C*************************************************************
C    ..................................................................
C E C H O _ G R I Z Z L Y _ D A T A *
C    ..................................................................
C************************************
      SUBROUTINE ECHO_GRIZZLY_DATA( IOSTAT )
C
C  9 Oct 98   Initial edit
C
C     This routine echos the Grizzly API input data to system output.
C
      IMPLICIT NONE
      INCLUDE 'grizapic.inc
      INTEGER IOSTAT
      INTEGER MMSG
      PARAMETER( MMSG = 10 )
      INTEGER I, IPDEPTH, IPSTREN, ISLPRY, ISOILT, ISTREN
      CHARACTER *50 ERRMSG(0:MMSG)
      DATA ERRMSG/
     & 'I/O error',
     & 'Premature E.O.F. reading input data',
     & 'No logical unit available for file I/O',
     & 'NSTREN out of range [2..MSTREN]',
     & 'NPDEPTH out of range [0..MPDEPTH]',
     & 'NPSTREN) out of range [2..MPSTREN]',
     & 'Unexpected soil type code reading vehicle data',
     & 'Soil strength mis-match reading vehicle data',
     & 'Unexpected soil type code reading plow data',
     & 'Soil strength mis-match reading plow data',
     & 'Unknown error'/
C
      NAMELIST /GRIZDATA/GCW, DIAG, HPCOEF, NPDEPTH, NPSTREN, NSTREN,
     &                    PDEPTHS, PSTRENS, STCOEF, STRENS
C
      IF( IOSTAT.NE.0 )THEN
        I=MIN(MAX(-IOSTAT,0),MMSG)
        WRITE(*,*)'Error reading "grizzly.dat" IOSTAT=',IOSTAT
        WRITE(*,*)CHARNB(ERRMSG(I))
      ELSE
        WRITE(*,GRIZDATA)
        WRITE(*,601)
  601   FORMAT(' ISLPRY ISTREN STRENS RESCOEF  TFOWMN  TFOWMX COEFFS')
        DO ISLPRY = 0, 1
          DO ISOILT = 1, MSOILS
            DO ISTREN = 1, NSTREN
              WRITE(*,602)ISLPRY,ISOILT,STRENS(ISTREN),
     &         RESCOEF(ISTREN,ISOILT,ISLPRY),
     &         TFOWMN(ISTREN,ISOILT,ISLPRY),
     &         TFOWMX(ISTREN,ISOILT,ISLPRY),
     &         (B(I,ISTREN,ISOILT,ISLPRY),I=1,3)
  602         FORMAT(1X,I4,I7,F8.1,F10.4,2F8.4,3G15.7)
            END DO
          END DO
```

```
         END DO
C
         WRITE(*,603)( PDEPTHS(IPDEPTH), IPDEPTH = 1, NPDEPTH )
  603    FORMAT(15X,'PDEPTHS'/' ISOILT PSTRENS',10F8.1)
         DO ISOILT = 1, MSOILS
           DO IPSTREN = 1, NPSTREN
             WRITE(*,604)ISOILT, PSTRENS(IPSTREN),
     &        (PFORCES(IPDEPTH,IPSTREN,ISOILT),
     &         IPDEPTH = 1, NPDEPTH )
  604        FORMAT(1X,I4,F8.1,10F8.1)
           END DO
         END DO
       END IF
C
       RETURN
       END
C IFIND Find subscript and interpolation factor of data in table 18 Nov
98
C*************************************************************
C          *
C I F I N D *
C          *
C************
       LOGICAL FUNCTION IFIND( I, FACT, DATA, ARRAY, NPTS )
C
C 19 Mar 91   Previous edit
C 18 Nov 98   Re-written for GRIZZLY API
C
C      This routine uses a binary search algorithm to locate the points
C      p(I) and p(I+1) that surround the input data point. The factor
C      needed for linear interpolation is then computed.  If IFIND is
.false.
C      then array contains just one point.  Otherwise interpolate using:
C      y = ( y(i+1) - y(i) ) * FACT + y(i)
C
C Inputs:
C      ARRAY     Array of data (1-dimension)
C      DATA      Data value to find
C      NPTS      Number of data elements in ARRAY
C
C Outputs:
C      I         Subscript of point in array such that data is between
C                point ARRAY(I) and ARRAY(I+1). Note: If point is less
than
C                or equal ARRAY(1), I=1; if point is greater than or
equal
C                to ARRAY(NPTS), I = NPTS-1.
C      IFIND     .TRUE. if NPTS > 1 and DATA is between ARRAY(1) and
C                ARRAY(NPTS) inclusive, else .FALSE.
C      FACT      Interpolation factor for data if IFIND = .TRUE.; else =
0.0
C
C Internal:
C      I1        Current index of array value > data
C      I2        Current index of array value < data
C
       IMPLICIT NONE
       INTEGER I, I1, I2, NPTS
       REAL ARRAY(NPTS), DATA, FACT
C
       IF(NPTS.LE.1)THEN
    I=1
```

```
     FACT=0.0
     IFIND=.FALSE.
       ELSE
         IF( ARRAY(NPTS) .GE. ARRAY(1) )THEN
C          Ascending order
       I1=1
       I2=NPTS
         ELSE
C          Descending order
       I1=NPTS
       I2=1
         END IF
         DO WHILE ( ABS(I2-I1) .GT. 1 )
           I=(I1+I2)/2
       IF( DATA .LT. ARRAY(I) )THEN
         I2=I
           ELSE IF( DATA .GT. ARRAY(I) )THEN
             I1=I
           ELSE
C            Exactly equal ARRAY(I)
             I1=I
             IF( I1.LT.NPTS )THEN
               I2 = I+1
             ELSE
               I2 = I-1
             END IF
             EXIT
           END IF
         END DO
C        Data is between ARRAY(I1) and ARRAY(I2)
         I=MIN0(I1,I2)
         I2=MAX0(I1,I2)
         FACT = ARRAY(I2)-ARRAY(I)
         IF( FACT .NE. 0.0 ) FACT = (DATA-ARRAY(I)) / FACT
         IFIND=.TRUE.
      END IF
      RETURN
      END
C LDEVUNQ Obtain a unique logical unit number
C*********************************************
C   *
C L D E V U N Q *
C   *
C****************
      INTEGER FUNCTION LDEVUNQ()
C
C  7 Oct 98     initial edit
C
C     This routine obtains an unused logical unit number for
C fortran I/O
C
C Output:
C     LDEVUNQ   Unused logical unit number or zero if none is available
C
      IMPLICIT NONE
      LOGICAL OPENED
      INTEGER L
      DO L = 1, 1024
   INQUIRE( UNIT=L, OPENED=OPENED )
        IF( .NOT. OPENED )THEN
     LDEVUNQ = L
          RETURN
```

```
  END IF
END DO
LDEVUNQ = 0
RETURN
END
```

Appendix B

GRIZZLY API Checkout Performance Data

```
! Grizzly performance results.  15 December 1998
! Power: 1500 hp, 125 Degrees, Sea-level, NBC-OFF
! Weight: 142760
! Plow data from Dr. Mason, WES
&GRIZDATA
 DIAG= .FALSE.
 GCW= 127451., HPCOEF= 1.000, STCOEF= 1.000
 NSTREN=    10
 STRENS= 300. 200. 150. 100. 80. 50. 40. 30. 25. 20
 NPSTREN=   10
 PSTRENS= 300.0 200.0 150.0 100.0  80.0  50.0  40.0  30.0  25.0  20.0
 NPDEPTH=   5
 PDEPTHS=   6.0  12.0  18.0  24.0  30.0
 /
  1  300. 0.06029 0.83026 0.03001   2.386131     -0.2477937E-01   2.503212
 24.39    0.29   41.04
  1  200. 0.06494 0.83491 0.03007   2.380699     -0.2461229E-01   2.482711
 23.49    0.29   41.05
  1  150. 0.06998 0.83706 0.03011   2.377874     -0.2451840E-01   2.473318
 22.50    0.29   41.06
  1  100. 0.08145 0.82001 0.03005   2.392947     -0.2486672E-01   2.549373
 20.21    0.28   41.03
  1   80. 0.09155 0.80501 0.03009   2.425041     -0.2542072E-01   2.683470
 18.14    0.24   41.00
  1   50. 0.13341 0.74284 0.02924   2.483928     -0.2743072E-01   2.951147
 12.36    0.27   40.88
  1   40. 0.17780 0.67695 0.02923   2.542589     -0.2844124E-01   3.360419
 8.08    0.24   40.72
  1   30. 0.32857 0.45336 0.02834   3.062254     -0.3837402E-01   6.035738
 3.60    0.19   39.86
  1   25. 0.57941 0.08198 0.02712   39.60506      0.3328510      -157.4801
 0.00   -0.39   27.94
  1   20. 0.85248 0.00000 0.00000  0.0000000      0.0000000       0.0000000
 0.00    0.00    0.00
  2  300. 0.06029 0.83026 0.03001   2.386131     -0.2477937E-01   2.503212
 24.39    0.29   41.04
  2  200. 0.06494 0.83491 0.03007   2.380699     -0.2461229E-01   2.482711
 23.49    0.29   41.05
  2  150. 0.06998 0.83706 0.03011   2.377874     -0.2451840E-01   2.473318
 22.50    0.29   41.06
  2  100. 0.08145 0.82001 0.03005   2.392947     -0.2486672E-01   2.549373
 20.21    0.28   41.03
  2   80. 0.09155 0.80501 0.03009   2.425041     -0.2542072E-01   2.683470
 18.14    0.24   41.00
  2   50. 0.13341 0.74284 0.02924   2.483928     -0.2743072E-01   2.951147
 12.36    0.27   40.88
  2   40. 0.17780 0.67695 0.02923   2.542589     -0.2844124E-01   3.360419
 8.08    0.24   40.72
  2   30. 0.32857 0.45336 0.02834   3.062254     -0.3837402E-01   6.035738
 3.60    0.19   39.86
  2   25. 0.57941 0.08198 0.02712   39.60506      0.3328510      -157.4801
 0.00   -0.39   27.94
  2   20. 0.85248 0.00000 0.00000  0.0000000      0.0000000       0.0000000
 0.00    0.00    0.00
  3  300. 0.06029 0.79697 0.03017   2.399057     -0.2476644E-01   2.629600
 24.39    0.29   41.04
  3  200. 0.06494 0.80161 0.02973   2.417768     -0.2560912E-01   2.638845
 23.49    0.28   41.05
  3  150. 0.06998 0.80355 0.02921   2.471952     -0.2721448E-01   2.756707
```

```
22.50    0.22   41.06
  3  100. 0.08145 0.78498 0.02922   2.449261    -0.2677252E-01   2.721935
20.19    0.30   41.02
  3   80. 0.09155 0.76898 0.02994   2.421088    -0.2543395E-01   2.741838
18.12    0.31   40.98
  3   50. 0.13341 0.70576 0.02945   2.488902    -0.2718630E-01   3.117707
12.32    0.28   40.83
  3   40. 0.17780 0.64398 0.02934   2.556455    -0.2848813E-01   3.550984
8.05    0.25   40.65
  3   30. 0.32857 0.46965 0.02932   2.905509    -0.3455392E-01   5.585680
3.65    0.18   39.90
  3   25. 0.57941 0.25243 0.02778   4.740184    -0.6354313E-01   14.37724
0.00    0.62   37.53
  3   20. 0.85248 0.02218 0.00000  0.0000000     0.0000000       0.0000000
0.00    0.00    0.00
  4  300. 0.07029 0.80697 0.03101   2.372528    -0.2331115E-01   2.612162
22.44    0.25   41.06
  4  200. 0.07494 0.81161 0.02929   2.440238    -0.2652041E-01   2.654501
21.52    0.26   41.07
  4  150. 0.07998 0.81355 0.02915   2.442688    -0.2671763E-01   2.645511
20.52    0.26   41.08
  4  100. 0.09145 0.79498 0.03010   2.402925    -0.2491242E-01   2.639429
18.17    0.29   41.04
  4   80. 0.10155 0.77898 0.02906   2.459738    -0.2714995E-01   2.752970
16.06    0.30   41.01
  4   50. 0.14341 0.71576 0.02949   2.479917    -0.2699084E-01   3.053029
11.32    0.29   40.86
  4   40. 0.18780 0.65398 0.02947   2.540812    -0.2807300E-01   3.470354
7.58    0.25   40.69
  4   30. 0.33857 0.47965 0.02947   2.868214    -0.3371206E-01   5.432723
3.57    0.15   39.96
  4   25. 0.58941 0.26243 0.02865   4.338891    -0.5693929E-01   12.96852
0.00    0.62   37.72
  4   20. 0.86248 0.03218 0.02873   2.328626     0.7384897E-01  -55.87772
0.00    0.00    4.27
  5  300. 0.14500 0.60096 0.02946   2.677331    -0.3027066E-01   4.050798
10.99    0.19   40.77
  5  200. 0.14500 0.60096 0.02946   2.677331    -0.3027066E-01   4.050798
10.99    0.19   40.77
  5  150. 0.14500 0.60096 0.02946   2.677331    -0.3027066E-01   4.050798
10.99    0.19   40.77
  5  100. 0.14500 0.60096 0.02946   2.677331    -0.3027066E-01   4.050798
10.99    0.19   40.77
  5   80. 0.14500 0.60096 0.02946   2.677331    -0.3027066E-01   4.050798
10.99    0.19   40.77
  5   50. 0.14500 0.57775 0.03009   2.672992    -0.2945804E-01   4.169206
10.97    0.23   40.72
  5   40. 0.14500 0.55275 0.02938   2.766574    -0.3192579E-01   4.463585
10.94    0.27   40.66
  5   30. 0.14500 0.52051 0.02937   2.823690    -0.3289561E-01   4.770657
10.91    0.33   40.58
  5   25. 0.14500 0.50008 0.02962   2.835485    -0.3272779E-01   4.957386
10.88    0.36   40.52
  5   20. 0.14500 0.47508 0.02939   2.963798    -0.3495865E-01   5.619157
10.84    0.19   40.44
  1  300. 0.07029 0.45195 0.02807   3.173107    -0.3827690E-01   6.295038
22.53    0.18   41.53
  1  200. 0.07494 0.45660 0.02814   3.151491    -0.3782472E-01   6.203522
21.61    0.17   41.57
  1  150. 0.07998 0.46164 0.02822   3.128604    -0.3734361E-01   6.106895
20.61    0.16   41.61
  1  100. 0.09145 0.47311 0.02911   3.009674    -0.3430128E-01   5.766220
18.29    0.17   41.70
  1   80. 0.10155 0.48321 0.02953   2.928677    -0.3245092E-01   5.477236
16.19    0.20   41.77
```

```
  1   50. 0.14341 0.52507 0.02932   2.845013     -0.3137165E-01   4.829613
11.50     0.28    42.05
  1   40. 0.18780 0.56945 0.02894   2.812172     -0.3118804E-01   4.466991
7.79      0.21    42.30
  1   30. 0.33857 0.46336 0.02825   3.120885     -0.3718080E-01   6.074362
3.51      0.16    41.62
  1   25. 0.58941 0.09198 0.02722   3610.466      -2.808330       1245.116
0.00     -0.26    28.17
  1   20. 0.86248 0.00000 0.00000  0.0000000      0.0000000      0.0000000
0.00      0.00     0.00
  2  300. 0.07029 0.38582 0.02805   3.462378     -0.4191734E-01   7.806674
22.52     0.29    41.68
  2  200. 0.07494 0.39046 0.02805   3.438879     -0.4156519E-01   7.666971
21.60     0.29    41.73
  2  150. 0.07998 0.39551 0.02809   3.411464     -0.4109797E-01   7.520333
20.60     0.29    41.79
  2  100. 0.09145 0.40698 0.02826   3.345922     -0.3986068E-01   7.204072
18.27     0.28    41.91
  2   80. 0.10155 0.41708 0.02846   3.287926     -0.3869227E-01   6.944306
16.18     0.27    42.02
  2   50. 0.14341 0.45894 0.02806   3.204469     -0.3776080E-01   6.285129
11.49     0.17    42.40
  2   40. 0.18780 0.50332 0.02965   2.898017     -0.3089056E-01   5.124012
7.78      0.30    42.74
  2   30. 0.33857 0.46336 0.02812   3.184410     -0.3734549E-01   6.199853
3.56      0.16    42.44
  2   25. 0.58941 0.09198 0.02730   1552.599      -1.811058       816.1611
0.00     -0.31    28.40
  2   20. 0.86248 0.00000 0.00000  0.0000000      0.0000000      0.0000000
0.00      0.00     0.00
  3  300. 0.07029 0.50667 0.02979   2.826057     -0.3119942E-01   4.927472
22.55     0.33    41.41
  3  200. 0.07494 0.51132 0.02899   2.884531     -0.3315166E-01   4.985970
21.63     0.31    41.43
  3  150. 0.07998 0.51636 0.02912   2.865999     -0.3268946E-01   4.910909
20.62     0.31    41.46
  3  100. 0.09145 0.52784 0.02946   2.822073     -0.3155185E-01   4.746768
18.30     0.30    41.51
  3   80. 0.10155 0.53793 0.02977   2.782979     -0.3051055E-01   4.609594
16.20     0.29    41.56
  3   50. 0.14341 0.57979 0.02991   2.712021     -0.2909783E-01   4.233890
11.51     0.22    41.73
  3   40. 0.18780 0.62418 0.02940   2.675860     -0.2902573E-01   3.918372
7.79      0.18    41.88
  3   30. 0.33857 0.47965 0.02927   2.977709     -0.3422661E-01   5.633093
3.71      0.16    41.27
  3   25. 0.58941 0.26243 0.02846   4.541886     -0.5792575E-01   13.52588
0.00      0.65    39.05
  3   20. 0.86248 0.03218 0.02872   2.139589      0.7058474E-01  -55.70502
0.00      0.00     4.59
  4  300. 0.08329 0.55450 0.02818   2.852068     -0.3361849E-01   4.627240
19.97     0.22    41.53
  4  200. 0.08794 0.55915 0.02828   2.837002     -0.3322966E-01   4.572036
19.03     0.22    41.55
  4  150. 0.09298 0.56419 0.02893   2.780569     -0.3148460E-01   4.448465
17.99     0.22    41.58
  4  100. 0.10445 0.57567 0.02978   2.702935     -0.2912363E-01   4.254528
14.82     0.21    41.63
  4   80. 0.11455 0.58576 0.03005   2.671063     -0.2824027E-01   4.146077
14.03     0.20    41.68
  4   50. 0.15641 0.62763 0.02911   2.665629     -0.2917025E-01   3.871513
9.33      0.19    41.86
  4   40. 0.20080 0.66698 0.03038   2.539699     -0.2552110E-01   3.414149
7.18      0.25    42.02
  4   30. 0.35157 0.49265 0.02944   2.852153     -0.3212024E-01   5.164587
```

```
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0.00     0.44    38.64
  4   20. 0.87548 0.04518 0.02841   6.258889       0.1249727      -78.43407
0.00     0.00    13.61
  5  300. 0.14500 0.60096 0.02946   2.677331      -0.3027066E-01   4.050798
10.99     0.19    40.77
  5  200. 0.14500 0.60096 0.02946   2.677331      -0.3027066E-01   4.050798
10.99     0.19    40.77
  5  150. 0.14500 0.60096 0.02946   2.677331      -0.3027066E-01   4.050798
10.99     0.19    40.77
  5  100. 0.14500 0.60096 0.02946   2.677331      -0.3027066E-01   4.050798
10.99     0.19    40.77
  5   80. 0.14500 0.60096 0.02946   2.677331      -0.3027066E-01   4.050798
10.99     0.19    40.77
  5   50. 0.14500 0.57775 0.03009   2.672992      -0.2945804E-01   4.169206
10.97     0.23    40.72
  5   40. 0.14500 0.55275 0.02938   2.766574      -0.3192579E-01   4.463585
10.94     0.27    40.66
  5   30. 0.14500 0.52051 0.02937   2.823690      -0.3289561E-01   4.770657
10.91     0.33    40.58
  5   25. 0.14500 0.50008 0.02962   2.835485      -0.3272779E-01   4.957386
10.88     0.36    40.52
  5   20. 0.14500 0.47508 0.02939   2.963798      -0.3495865E-01   5.619157
10.84     0.19    40.44
  1  300.   50596.   99408. 143881. 189690. 236837.
  1  200.   33430.   66165.   95168. 125508. 157185.
  1  150.   24692.   49226.   70337.   92784. 116568.
  1  100.   16410.   33373.   47222.   62409.   78932.
  1   80.   12857.   26534.   37226.   49255.   62621.
  1   50.    7996.   17375.   23963.   31888.   41150.
  1   40.    6133.   13861.   18870.   25217.   32900.
  1   30.    4528.   10922.   14669.   19753.   26173.
  1   25.    3698.    9424.   12539.   16991.   22781.
  1   20.    3211.    8594.   11393.   15530.   21003.
  2  300.   33123.   51724.   64335.   77689.   91785.
  2  200.   22268.   35673.   43976.   53022.   62809.
  2  150.   16612.   27289.   33325.   40103.   47622.
  2  100.   10937.   18885.   22653.   27163.   32415.
  2   80.    8655.   15509.   18370.   21973.   26319.
  2   50.    5685.   11159.   12887.   15356.   18567.
  2   40.    4525.    9451.   10725.   12740.   15498.
  2   30.    3348.    7724.    8544.   10106.   12410.
  2   25.    2747.    6847.    7441.    8776.   10854.
  2   20.    2133.    5956.    6323.    7431.    9282.
  3  300.   25835.   34381.   38206.   43161.   49247.
  3  200.   17728.   24509.   27387.   31395.   36533.
  3  150.   12756.   18412.   20659.   24035.   28542.
  3  100.    9615.   14630.   16561.   19622.   23813.
  3   80.    7237.   11707.   13322.   16067.   19942.
  3   50.    4311.    8152.    9361.   11670.   15079.
  3   40.    3535.    7229.    8213.   10224.   13263.
  3   30.    2727.    6269.    6988.    8655.   11268.
  3   25.    2319.    5785.    6357.    7832.   10212.
  3   20.    1877.    5261.    5656.    6905.    9008.
  4  300.   47912.   89417. 126836. 165732. 206104.
  4  200.   31768.   59826.   84510. 110671. 138308.
  4  150.   23670.   45002.   63319.   83112. 104381.
  4  100.   15521.   30123.   42072.   55497.   70399.
  4   80.   12294.   24273.   33746.   44695.   57121.
  4   50.    7550.   15768.   21703.   29115.   38003.
  4   40.    6055.   13137.   18011.   24361.   32188.
  4   30.    4525.   10469.   14282.   19571.   26336.
  4   25.    3511.    8698.   11803.   16385.   22443.
  4   20.    2918.    7717.   10468.   14696.   20401.
```

5	300.	44901.	78946.	108850.	140477.	173829.
5	200.	29727.	52954.	72866.	94503.	117863.
5	150.	22112.	39929.	54845.	71486.	89850.
5	100.	14444.	26844.	36765.	48410.	61779.
5	80.	11428.	21738.	29738.	39461.	50909.
5	50.	7054.	14424.	19733.	26767.	35524.
5	40.	5724.	12246.	16787.	23052.	31041.
5	30.	4370.	10042.	13815.	19311.	26532.
5	25.	3677.	8923.	12311.	17423.	24260.
5	20.	2962.	7781.	10785.	15513.	21965.

Appendix C
Real-Time Mobility DATA File for SAF

GRIZZLY API Checkout Performance Data

```
! Grizzly performance results.  15 December 1998
! Power: 1500 hp, 125 Degrees, Sea-level, NBC-OFF
! Weight: 142760
! Plow data from Dr. Mason, WES
&GRIZDATA
 DIAG= .FALSE.
 GCW= 127451., HPCOEF= 1.000, STCOEF= 1.000
 NSTREN=   10
 STRENS= 300. 200. 150. 100. 80. 50. 40. 30. 25. 20
 NPSTREN=  10
 PSTRENS= 300.0 200.0 150.0 100.0  80.0  50.0  40.0  30.0  25.0  20.0
 NPDEPTH=  5
 PDEPTHS=   6.0  12.0  18.0  24.0  30.0
/
1 300. 0.06029 0.83026 0.03001  2.386131  -0.2477937E-01  2.503212  24.39  0.29  41.04
1 200. 0.06494 0.83491 0.03007  2.380699  -0.2461229E-01  2.482711  23.49  0.29  41.05
1 150. 0.06998 0.83706 0.03011  2.377874  -0.2451840E-01  2.473318  22.50  0.29  41.06
1 100. 0.08145 0.82001 0.03005  2.392947  -0.2486672E-01  2.549373  20.21  0.28  41.03
1  80. 0.09155 0.80501 0.03009  2.425041  -0.2542072E-01  2.683470  18.14  0.24  41.00
1  50. 0.13341 0.74284 0.02924  2.483928  -0.2743072E-01  2.951147  12.36  0.27  40.88
1  40. 0.17780 0.67695 0.02923  2.542589  -0.2844124E-01  3.360419   8.08  0.24  40.72
1  30. 0.32857 0.45336 0.02834  3.062254  -0.3837402E-01  6.035738   3.60  0.19  39.86
1  25. 0.57941 0.08198 0.02712  39.60506   0.3328510   -157.4801    0.00 -0.39  27.94
1  20. 0.85248 0.00000 0.00000 0.0000000  0.0000000    0.0000000    0.00  0.00   0.00
2 300. 0.06029 0.83026 0.03001  2.386131  -0.2477937E-01  2.503212  24.39  0.29  41.04
2 200. 0.06494 0.83491 0.03007  2.380699  -0.2461229E-01  2.482711  23.49  0.29  41.05
2 150. 0.06998 0.83706 0.03011  2.377874  -0.2451840E-01  2.473318  22.50  0.29  41.06
2 100. 0.08145 0.82001 0.03005  2.392947  -0.2486672E-01  2.549373  20.21  0.28  41.03
2  80. 0.09155 0.80501 0.03009  2.425041  -0.2542072E-01  2.683470  18.14  0.24  41.00
2  50. 0.13341 0.74284 0.02924  2.483928  -0.2743072E-01  2.951147  12.36  0.27  40.88
2  40. 0.17780 0.67695 0.02923  2.542589  -0.2844124E-01  3.360419   8.08  0.24  40.72
2  30. 0.32857 0.45336 0.02834  3.062254  -0.3837402E-01  6.035738   3.60  0.19  39.86
2  25. 0.57941 0.08198 0.02712  39.60506   0.3328510   -157.4801   0.00 -0.39  27.94
2  20. 0.85248 0.00000 0.00000 0.0000000  0.0000000    0.0000000   0.00  0.00  0.00
3 300. 0.06029 0.79697 0.03017  2.399057  -0.2476644E-01  2.629600  24.39  0.29  41.04
3 200. 0.06494 0.80161 0.02973  2.417768  -0.2560912E-01  2.638845  23.49  0.28  41.05
3 150. 0.06998 0.80355 0.02921  2.471952  -0.2721448E-01  2.756707  22.50  0.22  41.06
3 100. 0.08145 0.78498 0.02922  2.449261  -0.2677252E-01  2.721935  20.19  0.30  41.02
3  80. 0.09155 0.76898 0.02994  2.421088  -0.2543395E-01  2.741838  18.12  0.31  40.98
```

3	50.	0.13341	0.70576	0.02945	2.488902	-0.2718630E-01	3.117707	12.32	0.28	40.83
3	40.	0.17780	0.64398	0.02934	2.556455	-0.2848813E-01	3.550984	8.05	0.25	40.65
3	30.	0.32857	0.46965	0.02932	2.905509	-0.3455392E-01	5.585680	3.65	0.18	39.90
3	25.	0.57941	0.25243	0.02778	4.740184	-0.6354313E-01	14.37724	0.00	0.62	37.53
3	20.	0.85248	0.02218	0.00000	0.0000000	0.0000000	0.0000000	0.00	0.00	0.00
4	300.	0.07029	0.80697	0.03101	2.372528	-0.2331115E-01	2.612162	22.44	0.25	41.06
4	200.	0.07494	0.81161	0.02929	2.440238	-0.2652041E-01	2.654501	21.52	0.26	41.07
4	150.	0.07998	0.81355	0.02915	2.442688	-0.2671763E-01	2.645511	20.52	0.26	41.08
4	100.	0.09145	0.79498	0.03010	2.402925	-0.2491242E-01	2.639429	18.17	0.29	41.04
4	80.	0.10155	0.77898	0.02906	2.459738	-0.2714995E-01	2.752970	16.06	0.30	41.01
4	50.	0.14341	0.71576	0.02949	2.479917	-0.2699084E-01	3.053029	11.32	0.29	40.86
4	40.	0.18780	0.65398	0.02947	2.540812	-0.2807300E-01	3.470354	7.58	0.25	40.69
4	30.	0.33857	0.47965	0.02947	2.868214	-0.3371206E-01	5.432723	3.57	0.15	39.96
4	25.	0.58941	0.26243	0.02865	4.338891	-0.5693929E-01	12.96852	0.00	0.62	37.72
4	20.	0.86248	0.03218	0.02873	2.328626	0.7384897E-01	-55.87772	0.00	0.00	4.27
5	300.	0.14500	0.60096	0.02946	2.677331	-0.3027066E-01	4.050798	10.99	0.19	40.77
5	200.	0.14500	0.60096	0.02946	2.677331	-0.3027066E-01	4.050798	10.99	0.19	40.77
5	150.	0.14500	0.60096	0.02946	2.677331	-0.3027066E-01	4.050798	10.99	0.19	40.77
5	100.	0.14500	0.60096	0.02946	2.677331	-0.3027066E-01	4.050798	10.99	0.19	40.77
5	80.	0.14500	0.60096	0.02946	2.677331	-0.3027066E-01	4.050798	10.99	0.19	40.77
5	50.	0.14500	0.57775	0.03009	2.672992	-0.2945804E-01	4.169206	10.97	0.23	40.72
5	40.	0.14500	0.55275	0.02938	2.766574	-0.3192579E-01	4.463585	10.94	0.27	40.66
5	30.	0.14500	0.52051	0.02937	2.823690	-0.3289561E-01	4.770657	10.91	0.33	40.58
5	25.	0.14500	0.50008	0.02962	2.835485	-0.3272779E-01	4.957386	10.88	0.36	40.52
5	20.	0.14500	0.47508	0.02939	2.963798	-0.3495865E-01	5.619157	10.84	0.19	40.44
1	300.	0.07029	0.45195	0.02807	3.173107	-0.3827690E-01	6.295038	22.53	0.18	41.53
1	200.	0.07494	0.45660	0.02814	3.151491	-0.3782472E-01	6.203522	21.61	0.17	41.57
1	150.	0.07998	0.46164	0.02822	3.128604	-0.3734361E-01	6.106895	20.61	0.16	41.61
1	100.	0.09145	0.47311	0.02911	3.009674	-0.3430128E-01	5.766220	18.29	0.17	41.70
1	80.	0.10155	0.48321	0.02953	2.928677	-0.3245092E-01	5.477236	16.19	0.20	41.77
1	50.	0.14341	0.52507	0.02932	2.845013	-0.3137165E-01	4.829613	11.50	0.28	42.05
1	40.	0.18780	0.56945	0.02894	2.812172	-0.3118804E-01	4.466991	7.79	0.21	42.30
1	30.	0.33857	0.46336	0.02825	3.120885	-0.3718080E-01	6.074362	3.51	0.16	41.62
1	25.	0.58941	0.09198	0.02722	3610.466	-2.808330	1245.116	0.00	-0.26	28.17
1	20.	0.86248	0.00000	0.00000	0.0000000	0.0000000	0.0000000	0.00	0.00	0.00
2	300.	0.07029	0.38582	0.02805	3.462378	-0.4191734E-01	7.806674	22.52	0.29	41.68
2	200.	0.07494	0.39046	0.02805	3.438879	-0.4156519E-01	7.666971	21.60	0.29	41.73
2	150.	0.07998	0.39551	0.02809	3.411464	-0.4109797E-01	7.520333	20.60	0.29	41.79
2	100.	0.09145	0.40698	0.02826	3.345922	-0.3986068E-01	7.204072	18.27	0.28	41.91
2	80.	0.10155	0.41708	0.02846	3.287926	-0.3869227E-01	6.944306	16.18	0.27	42.02
2	50.	0.14341	0.45894	0.02806	3.204469	-0.3776080E-01	6.285129	11.49	0.17	42.40
2	40.	0.18780	0.50332	0.02965	2.898017	-0.3089056E-01	5.124012	7.78	0.30	42.74
2	30.	0.33857	0.46336	0.02812	3.184410	-0.3734549E-01	6.199853	3.56	0.16	42.44
2	25.	0.58941	0.09198	0.02730	1552.599	-1.811058	816.1611	0.00	-0.31	28.40
2	20.	0.86248	0.00000	0.00000	0.0000000	0.0000000	0.0000000	0.00	0.00	0.00
3	300.	0.07029	0.50667	0.02979	2.826057	-0.3119942E-01	4.927472	22.55	0.33	41.41
3	200.	0.07494	0.51132	0.02899	2.884531	-0.3315166E-01	4.985970	21.63	0.31	41.43
3	150.	0.07998	0.51636	0.02912	2.865999	-0.3268946E-01	4.910909	20.62	0.31	41.46
3	100.	0.09145	0.52784	0.02946	2.822073	-0.3155185E-01	4.746768	18.30	0.30	41.51
3	80.	0.10155	0.53793	0.02977	2.782979	-0.3051055E-01	4.609594	16.20	0.29	41.56
3	50.	0.14341	0.57979	0.02991	2.712021	-0.2909783E-01	4.233890	11.51	0.22	41.73
3	40.	0.18780	0.62418	0.02940	2.675860	-0.2902573E-01	3.918372	7.79	0.18	41.88
3	30.	0.33857	0.47965	0.02927	2.977709	-0.3422661E-01	5.633093	3.71	0.16	41.27
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Appendix D
Laboratory Data

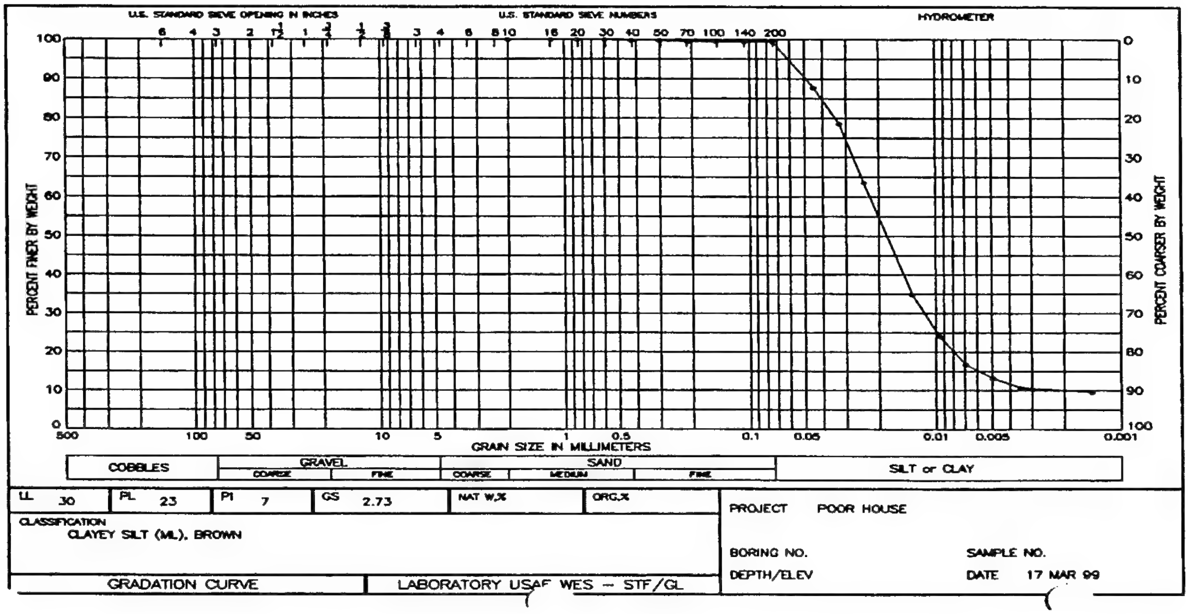

Figure D1. Gradation curves for Poor House property

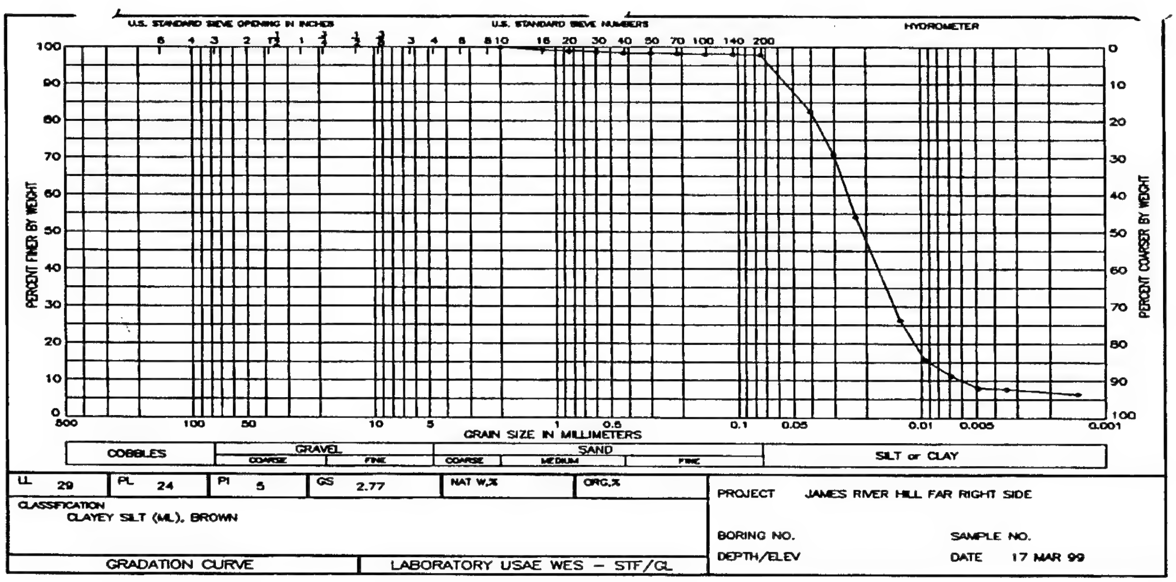

Figure D2. Gradation curve for Richards Hill

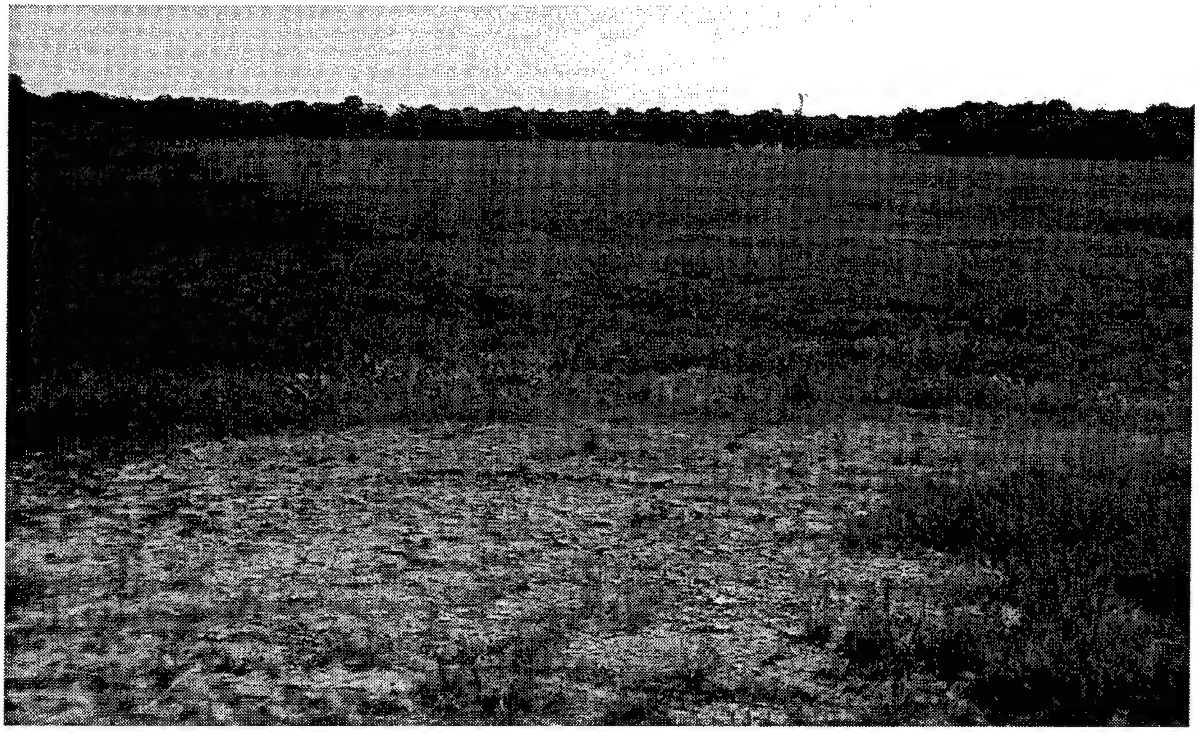

Figure D3. Photo of Fort Leonard Wood site

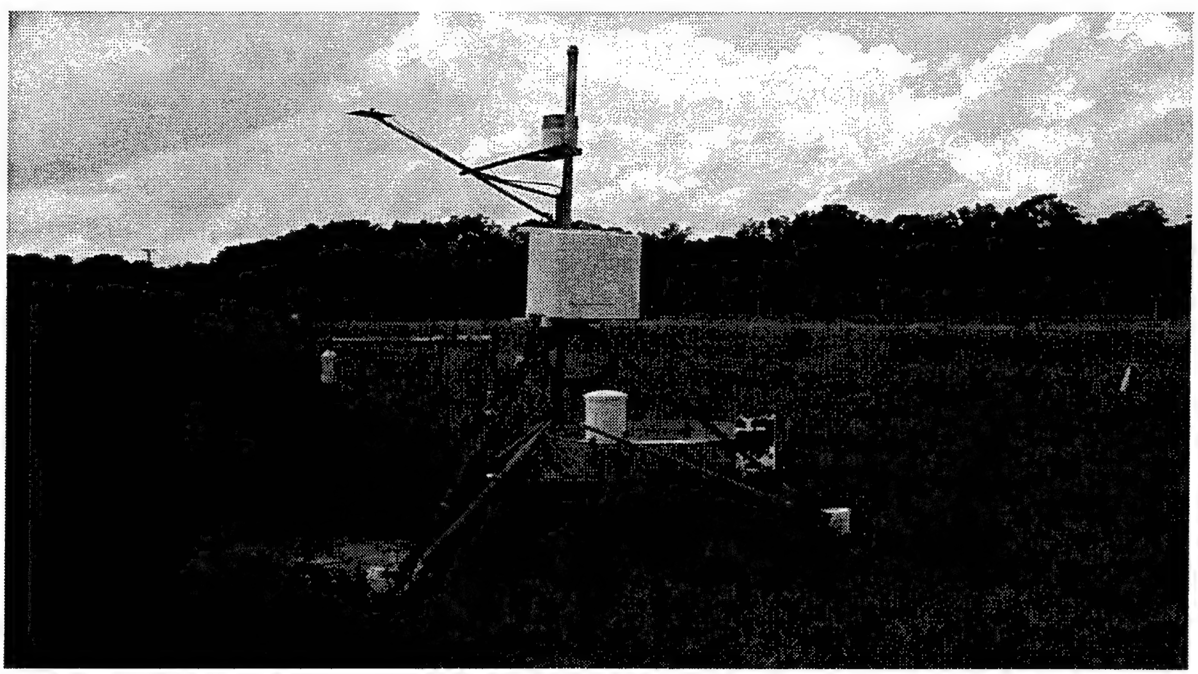

Figure D4. Photo of weather station

Appendix E Definitions

Following are definitions of terrain and vehicle terms, which are pertinent to this study. Unless otherwise referenced, they are extracted from the International Society of Terrain-Vehicle Systems Standards (Meyer et al.1977).[1]

Vehicle Terms

All-drive. Indicates that all of the axles (i.e., tires) are powered.

Contact pressure factor (CPF). A factor that is loosely related to the average hard-surface contact pressure under a vehicle. It is one of eight factors used to calculate the Mobility Index.

Mobility Index (MI). A parameter that is related to the VCI performance of vehicles on fine-grained soils. It was developed in the United States.

Mean Maximum Pressure (MMP). A parameter that is related to the average ground contact pressure under a vehicle and is used to represent soft-soil performance potential. It was developed in the United Kingdom.

Gross vehicle weight (GVW). The total weight of a vehicle.

Soil Terms

Trafficability. The ability of terrain to support the passage of vehicles.

Cone Index (CI). An index of soil shear strength obtained using a trafficability cone penetrometer standardized by the U.S. Army Engineer Research and Development Center (ERDC).

Remold Index (RI). An index of the sensitivity of soil to strength losses under vehicular traffic obtained using remolding equipment standardized by ERDC.

[1] References are listed following main text.

Rating Cone Index (RCI). An index of soil shear strength that includes consideration of the sensitivity of soil to strength losses under vehicular traffic. It is defined as the product of cone index and remold index for the particular layer of soil. For example, the 6-12 in. RCI equals the 6-12 in. RI times the 6-12 in. CI.

Cone penetrometer (see Figure E1). An instrument consisting of a circular cylindrical shaft (usually 18 to 36 in. in length) with a 30-deg right circular cone mounted on one end and a calibrated load-measuring device on the other end. For fine-grained soils, the shaft is 3/8-in.-diam steel (previously 5/8-in. aluminum) and the cone has a 0.5-sq-in. base area. The output measurement (CI) is the average of pressure readings (typically in pounds per square inch) taken at specified depths of penetration of the base of the cone into the soil. The depths of penetration used in the measurement are usually those taken at the top, midheight, and bottom of the critical layer. The pressure readings are the result of the penetration force divided by the base area of the cone with a standard penetration rate of 72 in. per minute.

Remolding equipment (see Figure E1). Equipment consisting of a circular cylindrical tube mounted on a steel base and a drop hammer. The tube has 1-7/8-in. inside diameter. The drop hammer weighs 2-1/2 lb and has 12 in. of drop travel. In use, soil samples approximately 6 in. in height are inserted into the tube using a trafficability (or Hvorslev) sampler. For fine-grained soils, cone index measurements are taken in the center of the sample before and after 100 blows of the drop hammer. The cone index measurements are based on readings taken in the sample at depths of 0, 1, 2, 3, and 4 in. The output measurement (RI) is the ratio of the cone index measurement after 100 blows over the cone index measurement before 100 blows. Trafficability (or Hvorslev) sampler (see Figure 2). A piston-type sampling device that is used to obtain an undisturbed sample in soft soils. It has a circular cylindrical tube with 1-7/8 in. inside diameter that is sharpened on the open end. The piston within the tube retracts during penetration into the soil such that a partial vacuum is maintained above the sample preserving the soil's in situ structure.

Critical layer. A layer of soil lying below the natural terrain surface that exerts the greatest influence on trafficability. The depth of the critical layer is dependent upon vehicle characteristics and the nature of the cone index (CI) profile with depth. A 6-in. layer of soil is typically used, but sometimes a 12-in. layer of soil is used. It is typically the 3- to 9-in. layer for light wheeled vehicles (wheel loads of 2,000 lb and less) and the 6- to 12-in. layer for normal wheeled vehicles (wheel loads up to about 10,000 lb).

Unified Soil Classification System (USCS). A system, which identifies (classifies) soils according to their textural and plasticity qualities and to their grouping with respect to their performances as engineering construction materials (Meyer et al. 1977).

Vehicle/Terrain Interaction Terms

Traction. The process by which a ground-based vehicle develops tractive force and overcomes motion resistance to produce desired motion relative to the terrain.

Tractive force (T). The force developed at the vehicle/terrain interface by the traction elements as a result of applied torque from the power plant.

Motion resistance (R). Any force imposing resistance against desired motion. For element-level traction considerations, it is composed of rolling resistance forces only.

Rolling resistance. Motion resistance that arises from deformations in the terrain (external) and the traction elements (internal).

Traction element. Any element of a vehicle that is designed to provide support and/or traction for a vehicle traveling on a surface (e.g. tires, tracks, feet, screws, etc.).

Drawbar (D). The amount of sustained towing force a self-propelled vehicle can produce. It is the resultant of tractive force reduced by motion resistance.

Drawbar coefficient (D/W). Drawbar divided by gross vehicle weight.

Vehicle Cone Index (VCI). Minimum soil strength necessary for a vehicle to make a specified number of passes. Consideration is most often given to 1 pass (VCI_1) and 50 passes (VCI_{50}).

Sinkage (z). The depth to which the traction elements penetrate the terrain measured normal to the original, undisturbed surface.

Slip. An indication of how the speed of the traction elements differs from the forward speed of the vehicle. It is defined by the equation (Meyer et al. 1977):

$$Slip = \left(\frac{r_R\omega - v}{r_R\omega} \right)$$

where: r_R = *rolling radius*
ω = *angular velocity of the wheel or number of revolutions per unit time divided by* 2π *for a track*
v = *forward velocity of vehicle or wheel axle*

Optimum slip. Slip at which maximum work index (WI) occurs.

Work Index (WI). A dimensionless number that represents the relative efficiency for a particular measure of drawbar. It is defined by the equation:

$$Work\ \ Index = \frac{D}{W}\left(1 - \frac{Slip\ (\%)}{100}\right)$$

Maximum pull slip. Slip at which maximum drawbar occurs.

Statistical Modeling Terms

Coefficient of determination (R). A measure of quality that indicates the amount of variation in the measurements (Y) that is accounted for by the relationship predictions. It is defined as the ratio of the explained variation in Y (i.e., the variation explained by) over the total variation in Y, and it is usually expressed in percent. It can be calculated using the equation:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}$$

where: i = *increment counter for the observations*
n = *total number of observations*
Y_i = *measured value for i-th observation*
$\hat{Y}_i$ = *predicted value for i=th observation*
$\overline{Y}$ = *mean measurement for all observations*

Degrees of freedom. A quantity related to quality that is equal to the total number of observations less the number of empirical constants.

Residual. The difference between measured (Y) and predicted (Y) values for an individual observation.

Standard error (S). A measure of quality that estimates the standard deviation of the measurements relative to the equation describing the relationship. It represents the amount of data scatter around the prediction equation. It can be calculated using the equation:

$$S_e = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n-k}}$$

where: i = *increment counter for the observations*
n = *total number of observations*
k = *number of empirical constants in the prediction equations*
Y_i = *measured value for i-th observation*
$\hat{Y}_i$ = *predicted value for i=th observation*

Adjusted coefficient of determination. A measure of quality that is identical to R2 with the exception that it takes the degrees of freedom associated with the relationship into account. This measure of quality is more appropriate when comparing various relationships that have different degrees of freedom. It can be calculated using the equation:

$$Adj.\ R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}\left(\frac{n-1}{n-k}\right)$$

where:

i = *increment counter for the observations*
n = *total number of observations*
k = *number of empirical constants in the prediction equations*
Y_i = *measured value for i-th observation*
$\hat{Y}_i$ = *predicted value for i=th observation*
$\overline{Y}$ = *mean measurement for all observations*

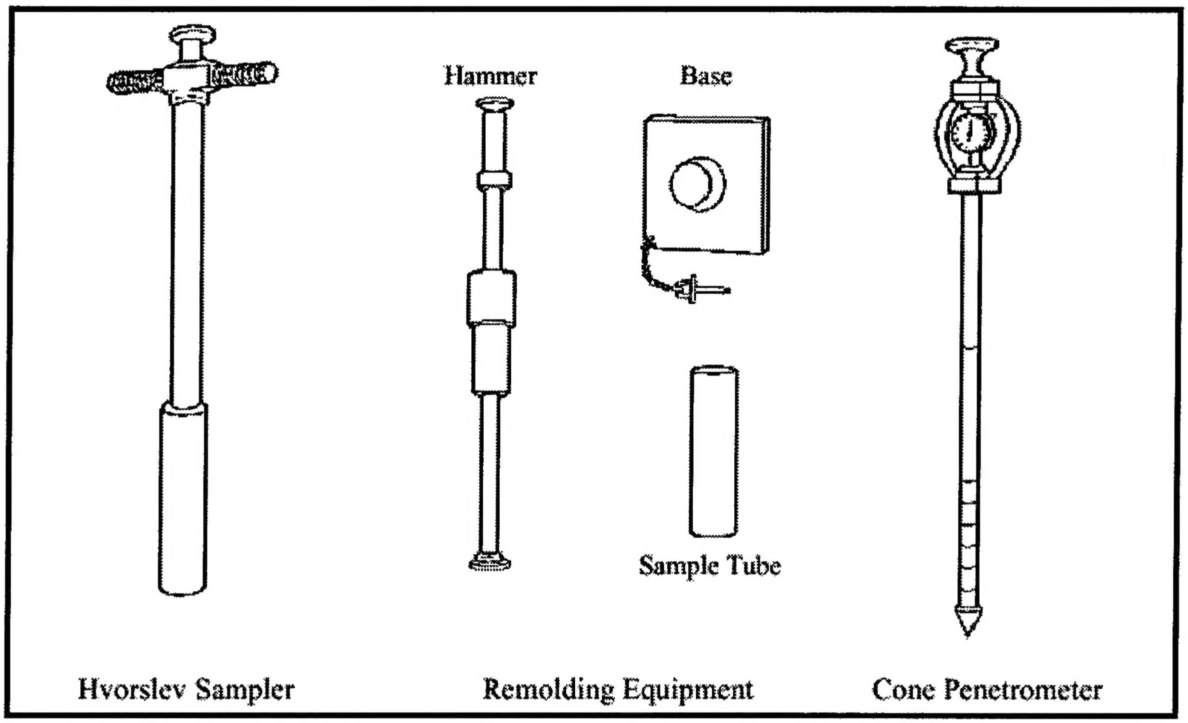

Figure E1. ERDC trafficability equipment

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14. ABSTRACT

The primary objective of this study was to extend current state of the art for predicting temporal changes in soil strength with time as it relates to vehicle traction. A secondary objective was to develop an algorithm which could be included in high-resolution combat models for improvement of modeling mobility. To this end, the algorithms developed in this study were included in the Semiautomated Forces (SAF) models, specifically JointSAF 5.4. This provided an approach to evaluating combat models in the context of weather effects on mobility.

Two models are developed. The first is the Short-Term Operational Forecasts of Trafficability (SOFT) model. The second Real-Time Mobility (RTM) Model is a vehicle movement model which reacts to continuous changes in soil strength.

15. SUBJECT TERMS

Combat model	Soft soil
Mobility	Soil moisture

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